



# Compact, Engineered, 2-Micron Coherent Doppler Wind Lidar Prototype for Field and Airborne Validation

IIP-04-0072

“Doppler Aerosol WiNd lidar (DAWN)”

Interim Review #1 (6 months)

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23 June 2006





# IIP Key Personnel

Dr. Michael J. Kavaya	NASA LaRC	PI
Dr. Farzin Amzajerian	NASA LaRC	Co-I, coherent lidar receiver lead
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Mr. Ed A. Modlin	NASA LaRC	Technician
Dr. Upendra N. Singh	NASA LaRC	Co-I, LRRP PI
Mr. Bo. C. Trieu	NASA LaRC	Mechanical and system engineering
Dr. Jirong Yu	NASA LaRC	Co-I, pulsed transmitter laser lead
Dr. Yingxin Bai	SAIC	Laser design
Mr. Mulugeta Petros	STC	Laser design
Mr. Paul Petzar	SAIC	Electronic Design
Mr. Karl Reithmaier	SAIC	Opto-mechanical design

Also many thanks to Brian Killough, Keith Murray, Garnett Hutchinson, and Ken Anderson



# IIP Motivation

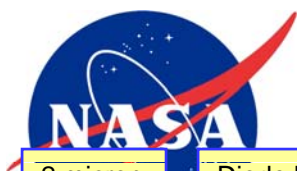
	Mission	Measurement	Technique	Technology
Primary	Science: Weather, Climate	Earth Vertical <b>Wind</b> Profiles	Scanning Doppler Lidar	Pulsed, 2-Micron, Ho Laser
Secondary	Science: Climate	Earth Vertical <b>CO<sub>2</sub></b> Concentration Profiles	Scanning DIAL Lidar	Pulsed, 2-Micron, Ho Laser
	Science & Exploration: Atmos. Char., EDL	Mars Vertical <b>Density</b> Profiles	DIAL Lidar (CO <sub>2</sub> )	Pulsed, 2-Micron, Ho Laser
	Science & Exploration: Atmos. Char., EDL	Mars Vertical <b>Wind</b> Profiles	Scanning Doppler Lidar	Pulsed, 2-Micron, Ho Laser
	Science: Climate	Earth Vertical <b>Aerosol</b> Concentration Profiles	Backscatter Lidar	Pulsed, 2-Micron, Ho Laser
	Science & Exploration: Atmos. Char., EDL	Mars Vertical <b>Dust</b> Profiles	Backscatter Lidar	Pulsed, 2-Micron, Ho Laser



# IIP Abstract

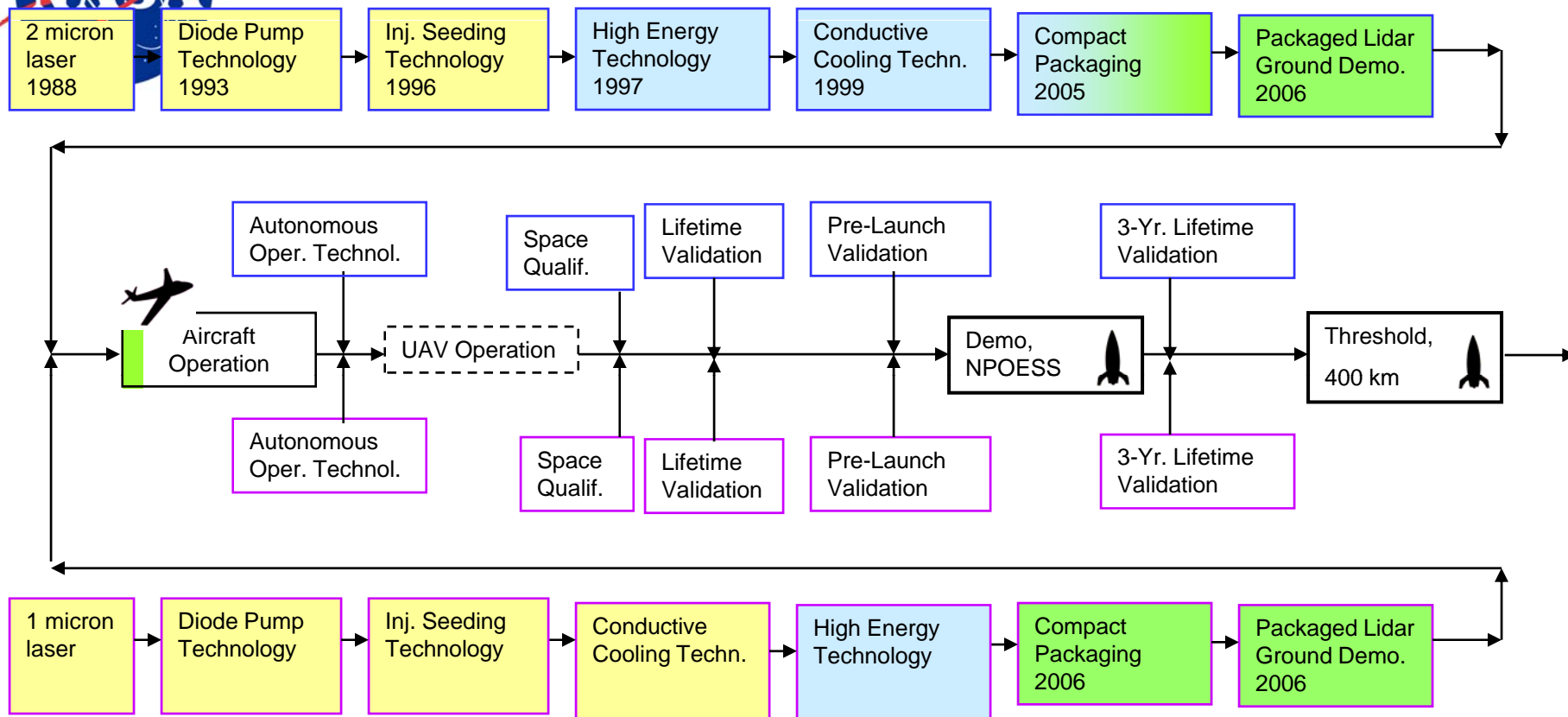
The state-of-the-art 2-micron coherent Doppler wind lidar breadboard at NASA/LaRC will be engineered and compactly packaged consistent with future aircraft flights. The packaged transceiver will be integrated into a coherent Doppler wind lidar system test bed at LaRC. Atmospheric wind measurements will be made to validate the packaged technology.

This will greatly advance the coherent part of the hybrid Doppler wind lidar solution to the need for global tropospheric wind measurements.

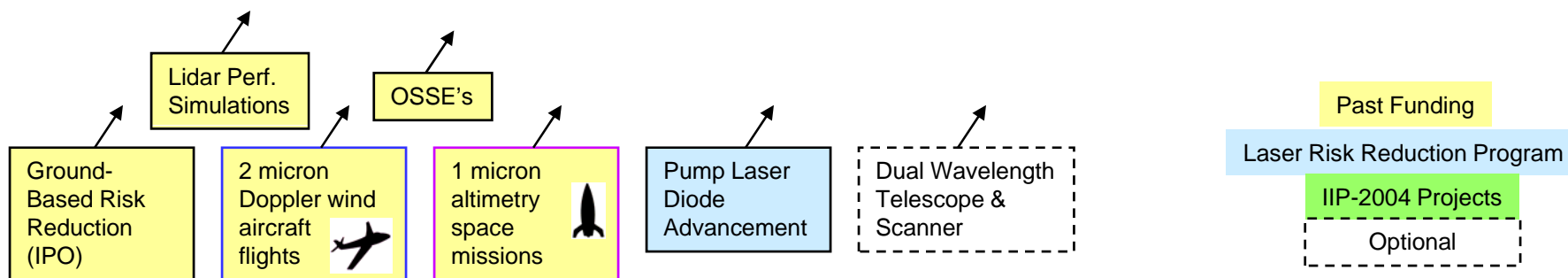


# IIP and the Global Tropospheric Wind Profiles Roadmap

## 2-Micron Coherent Doppler Lidar



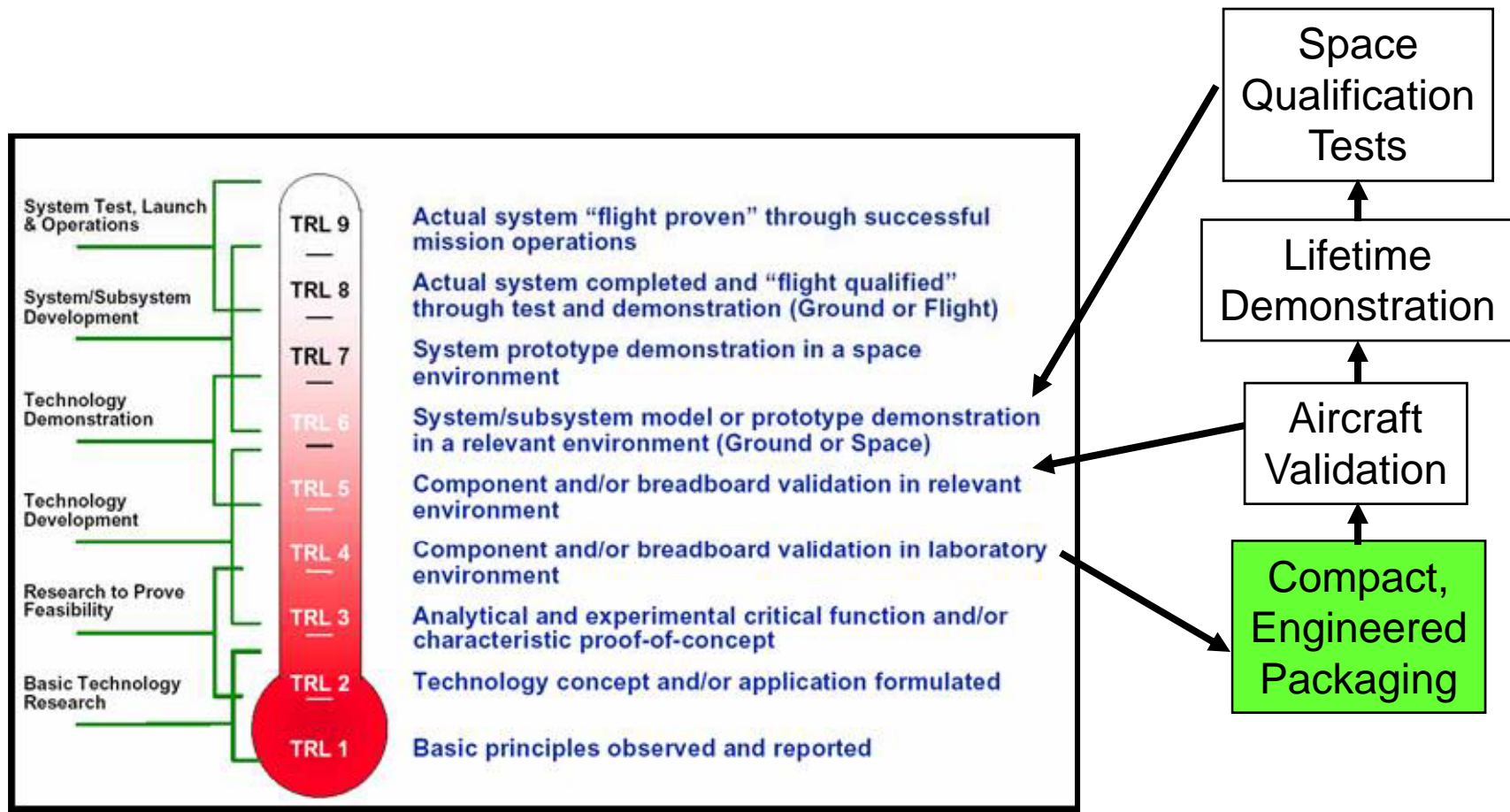
## 0.355-Micron Direct Doppler Lidar





# IIP TRL Advancement

“4 → 5”





# IIP and the LaRC Development of Pulsed, 2-Micron Laser Technology For Space

Category	Sub-Category/Date	6/02	9/02	2/03	4/03	11/03	2/05	12/05	LRRP	IIP	SPACE DEMO
<b>Demonstrated (Side-Pumped, LuLiF)</b>	Pulse Energy (J) (in double pulse)	0.135	0.355 /0.6	0.095	0.626/ 1.05	0.1/ 0.073	1/1.5	1.2		<b>0.25</b>	0.25
	Pulse Rate (Hz)	2	2	10	2	2/10	2	2		<b>10</b>	5-10
	Efficiency (%) (O-O)	3.65	3.66	2.57	4.10	2.78	5/6.2	6.5			
<b>Laser Component</b>	Oscillator	✓	✓	✓	✓	✓	✓	✓		✓	✓
	Preamplifier						✓				
	Amplifiers		1 x 2-pass		2 x 2-pass		2 x 2-pass	2 x 2-pass	✓	<b>1 x 2-pass</b>	1 x 2-pass
<b>Laser Mode</b>	Q-Switched	✓	✓	✓	✓	✓	✓	✓		✓	✓
	Double Q-Switched		✓		✓	✓	✓				
	Injection Seeded=SLM			✓						✓	✓
<b>Cooling</b>	All liquid				amp						
	Partially conductive	✓	✓	✓	osc		✓	✓		✓	
	All cond w/o heat pipe										
	All cond w/ heat pipe					✓			✓		✓
<b>Pump Diodes</b>	C Package				amp						
	A package	✓	✓	✓	osc	✓	✓	✓	✓		
	AA package									✓	
	G package										✓
<b>Packaging</b>	Laboratory Table	✓	✓	laser	✓	laser	✓	✓			
	Compact, Engineered			head		head			head	✓	✓



# IIP Re-Plan, Fall 2005

	Original Plan	Proposed Replan	Citation/Notes
Contracts	\$1850K to Raytheon over 3 years (450/650/750) for packaging the lidar transceiver	\$1800K to in-house effort with small contracts as needed for packaging the lidar transceiver	IIP proposal, page 16
Starting Point	Some Raytheon IRAD spending during past few months	Completed compact design from \$600K LRRP task in FY05	ESTO e-books report LRRP-05-0011-A-OCT-2005 plus CDR at LaRC on 11/28/05
Lidar Transceiver Pulse Energy	Packaging 100 mJ design	Packaging 250 mJ design	Closer to space & more validation options with higher energy
Packaged Transceiver Specifications Guaranteed	No (contractor will not include IRAD in SOW per 12/2/05 comments on SOW)	Yes	See 12/2/05 comments on SOW from Raytheon
Hardened for Future Post-IIP Aircraft Flight	Not included in NASA funding; promised IRAD effort may do some hardening	Flight-designed; ready for passenger compartment flights; ready for 60 Kft pressure	Necessary for aircraft flight
Electronics Advancement	No planned effort	Yes, compact laser control electronics included; heading towards high altitude & autonomous operation electronics	Necessary for future high-altitude aircraft flight in external pod for space perspective validation
External-to-Transceiver Thermal Management	No work planned outside of packaged transceiver	Custom-designed chiller/pump in addition to packaged transceiver	Necessary for future aircraft flights
Autonomous Operation Sensors And Electronics	No planned effort	Novel quad detector in laser cavity to monitor alignment	Milestone towards auto-alignment maintenance of laser; required for high-altitude aircraft and space
Delivery Schedule	32 months after start	30 months after start	Earlier delivery allows more ground testing & validation

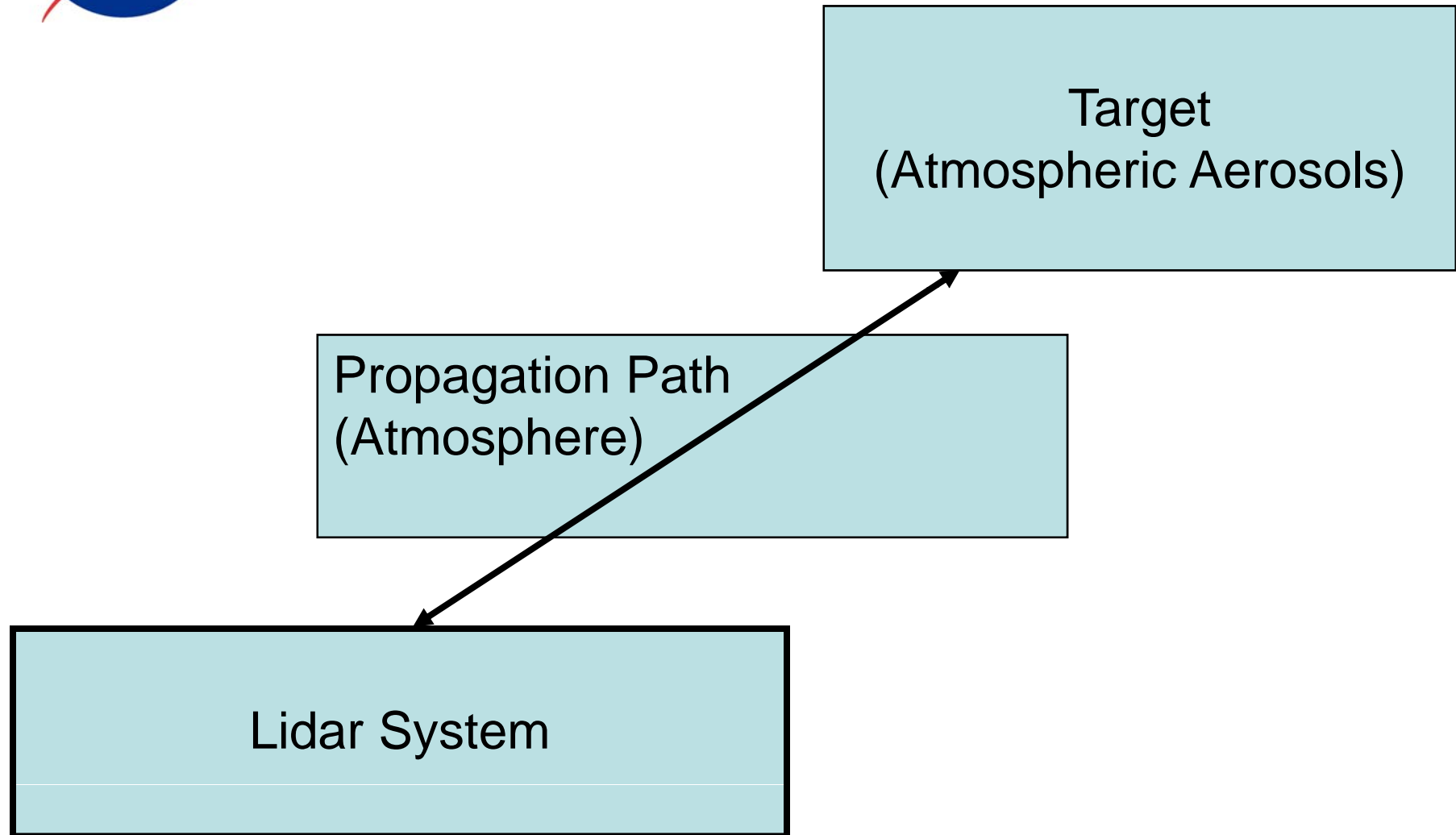




## IIP – Scope of the Effort

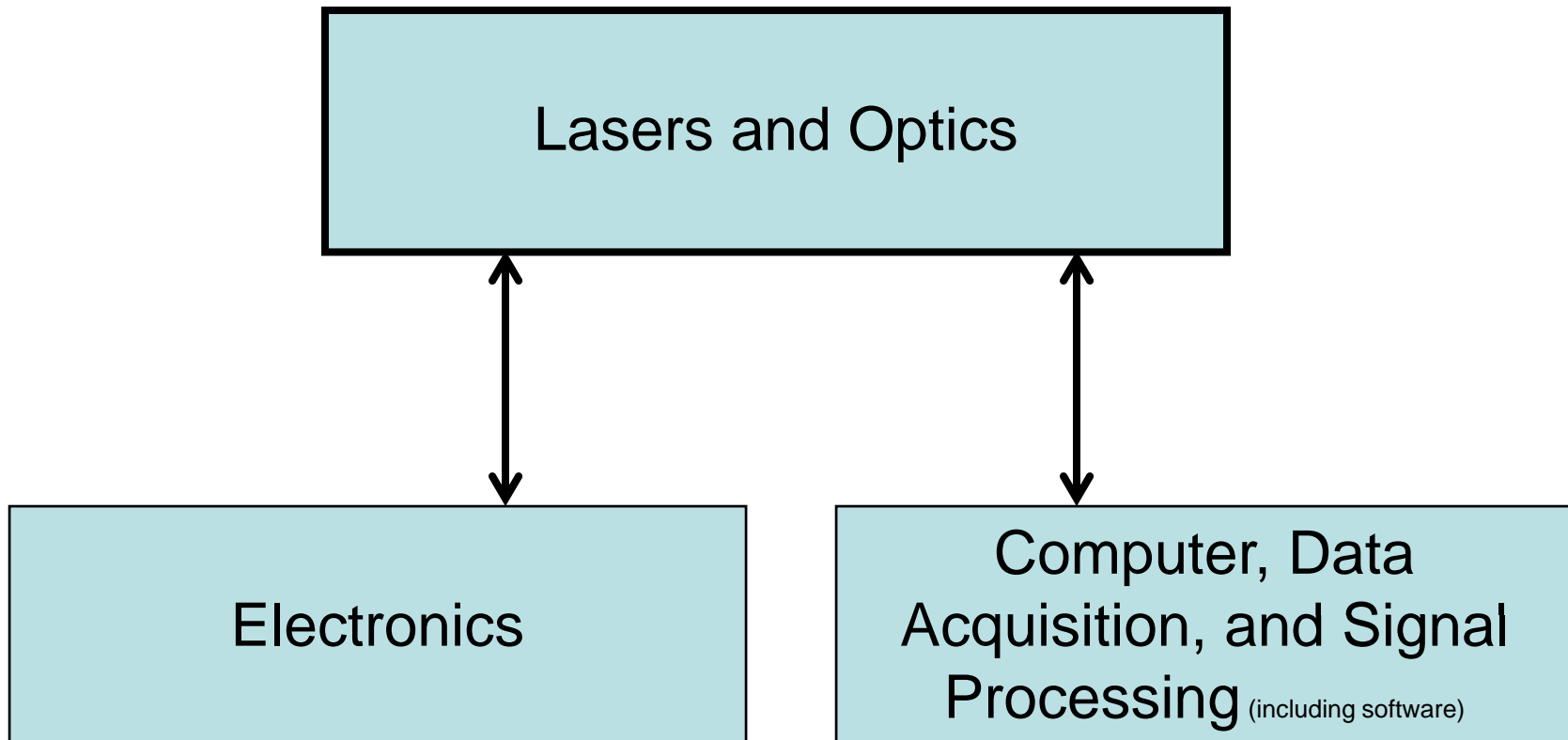


# Pulsed Doppler Wind Lidar Measurement Scenario



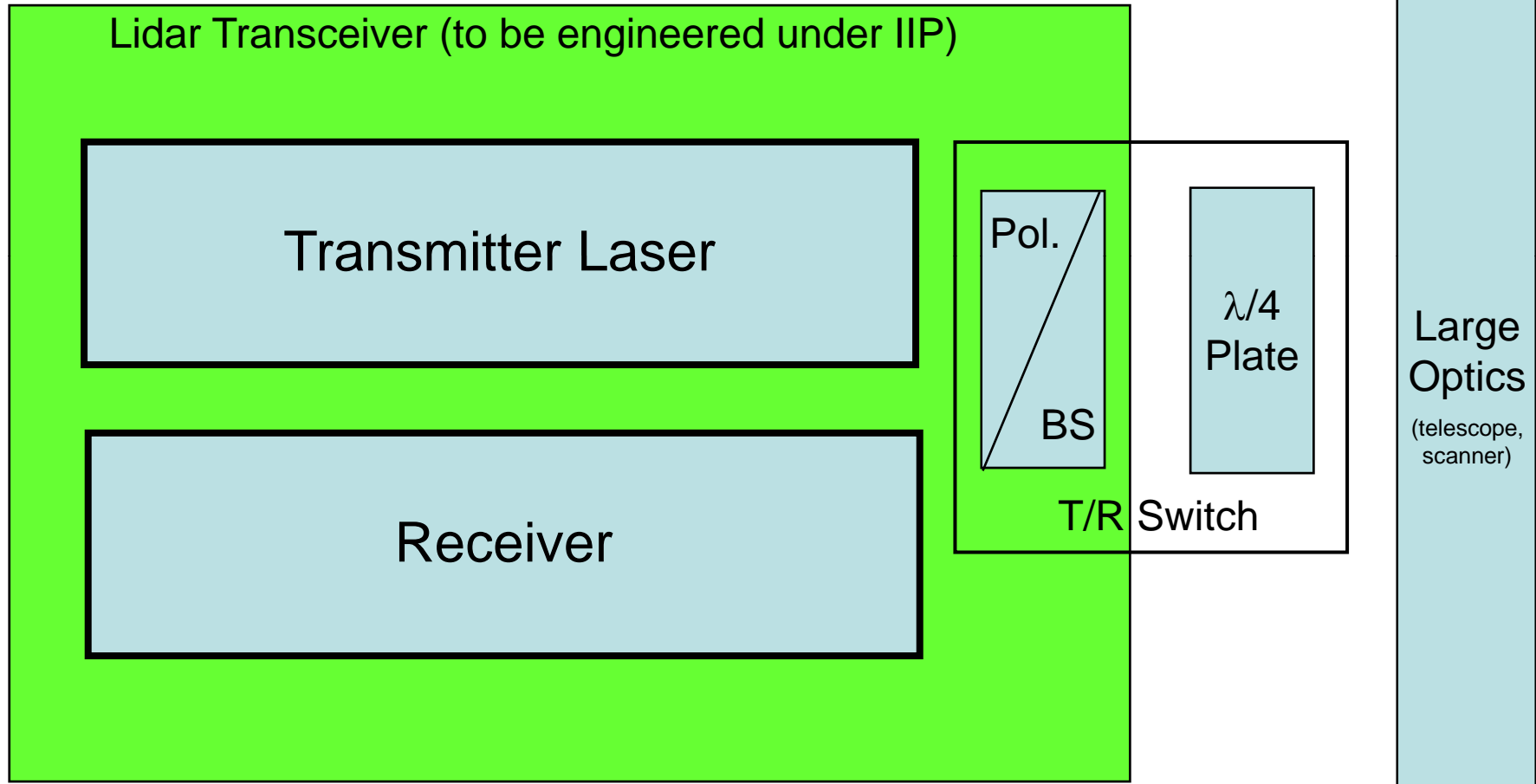


# Pulsed Doppler Wind Lidar System



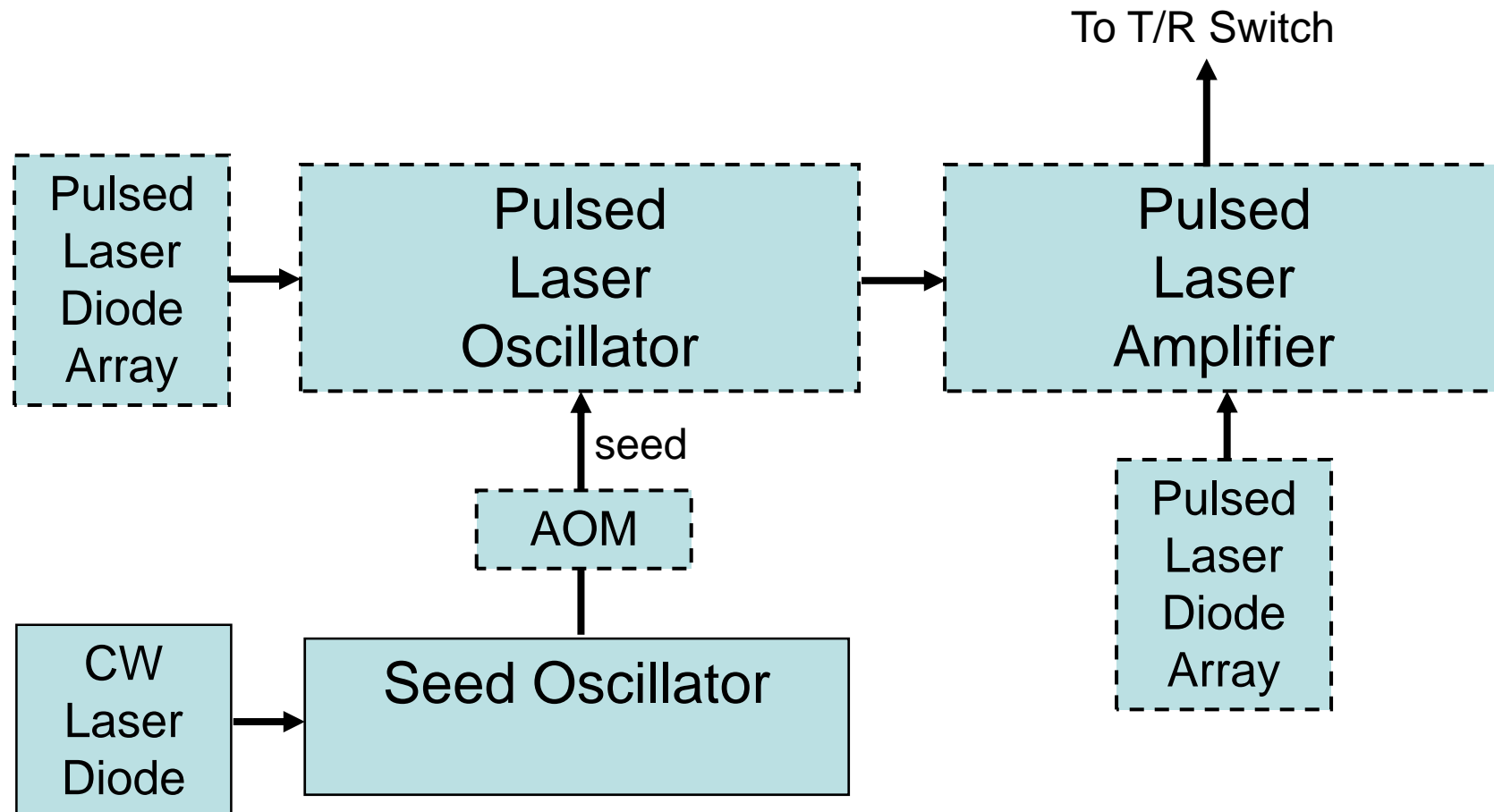


# Lasers and Optics Portion



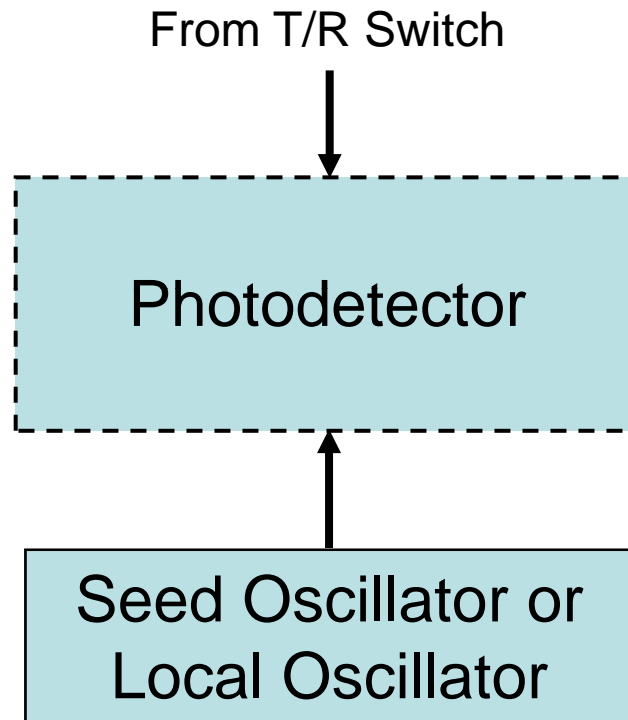


# Transmitter Laser



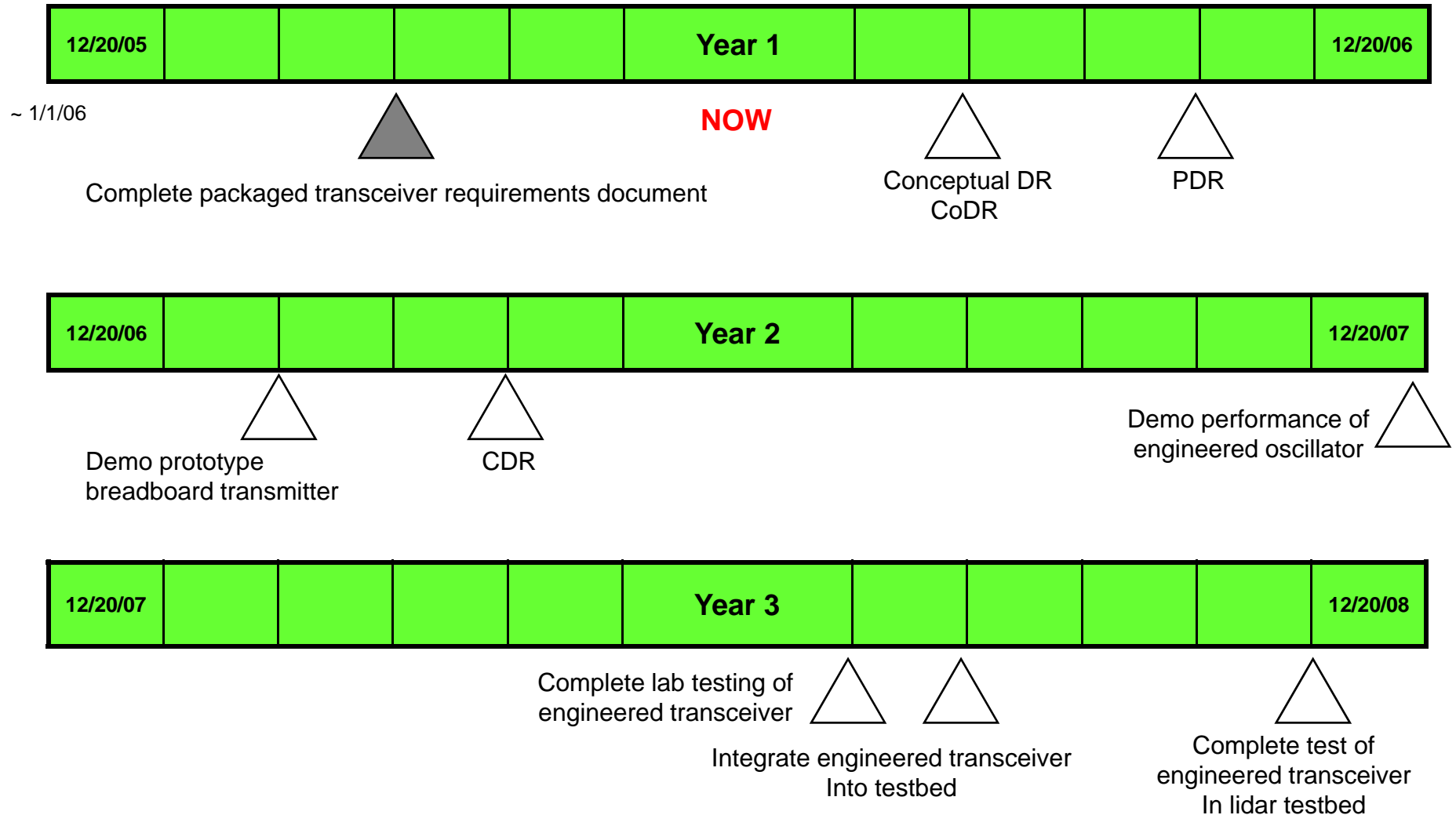


# Receiver





# IIP- Milestones & Schedule



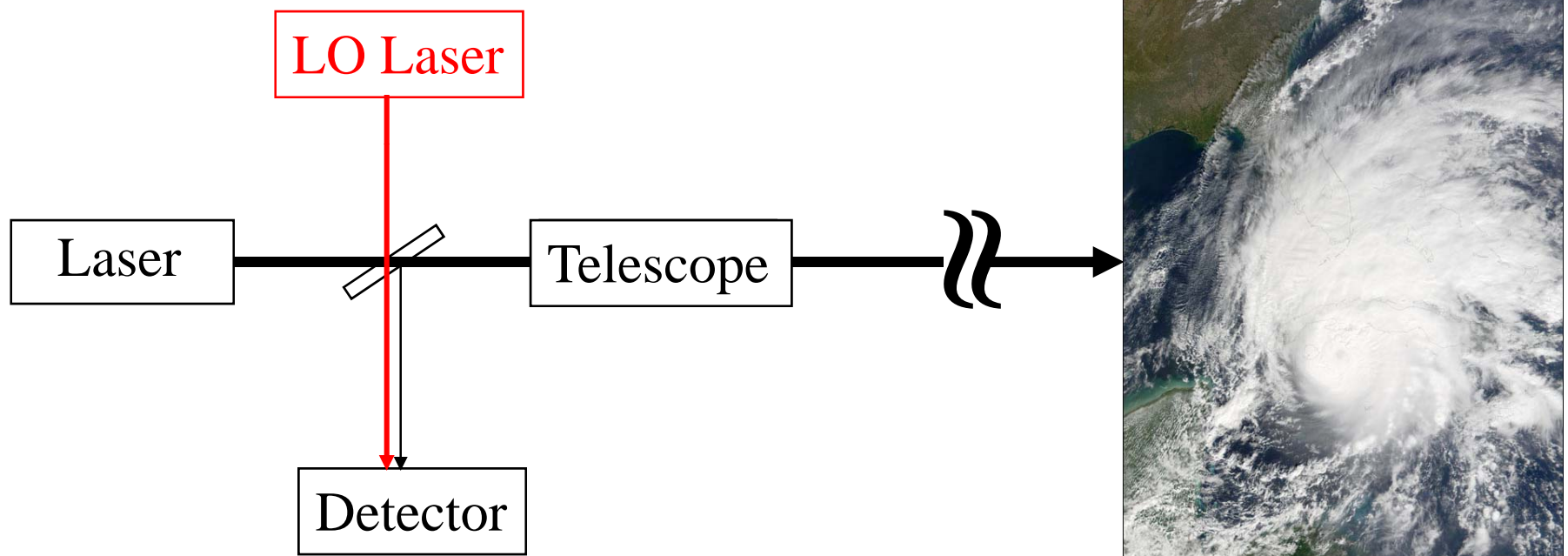


# Coherent Doppler Wind Lidar Technique





## What Is “Coherent” Lidar?





## Benefits Of The LO Laser

- Heterodyne gain effectively eliminates signal shot noise, thermal or Johnson noise, dark-current noise, and amplifier noise. LO spatial filtering eliminates background light noise
- Translation of optical frequency to radio frequency allows signal processing with mature and flexible electronics and software, and reduces  $1/f$  noise
- Extremely narrow bandpass filter using electronics or software rejects even more noise
- Frequency of beat signal is proportional to the target velocity - truly a direct measurement of velocity



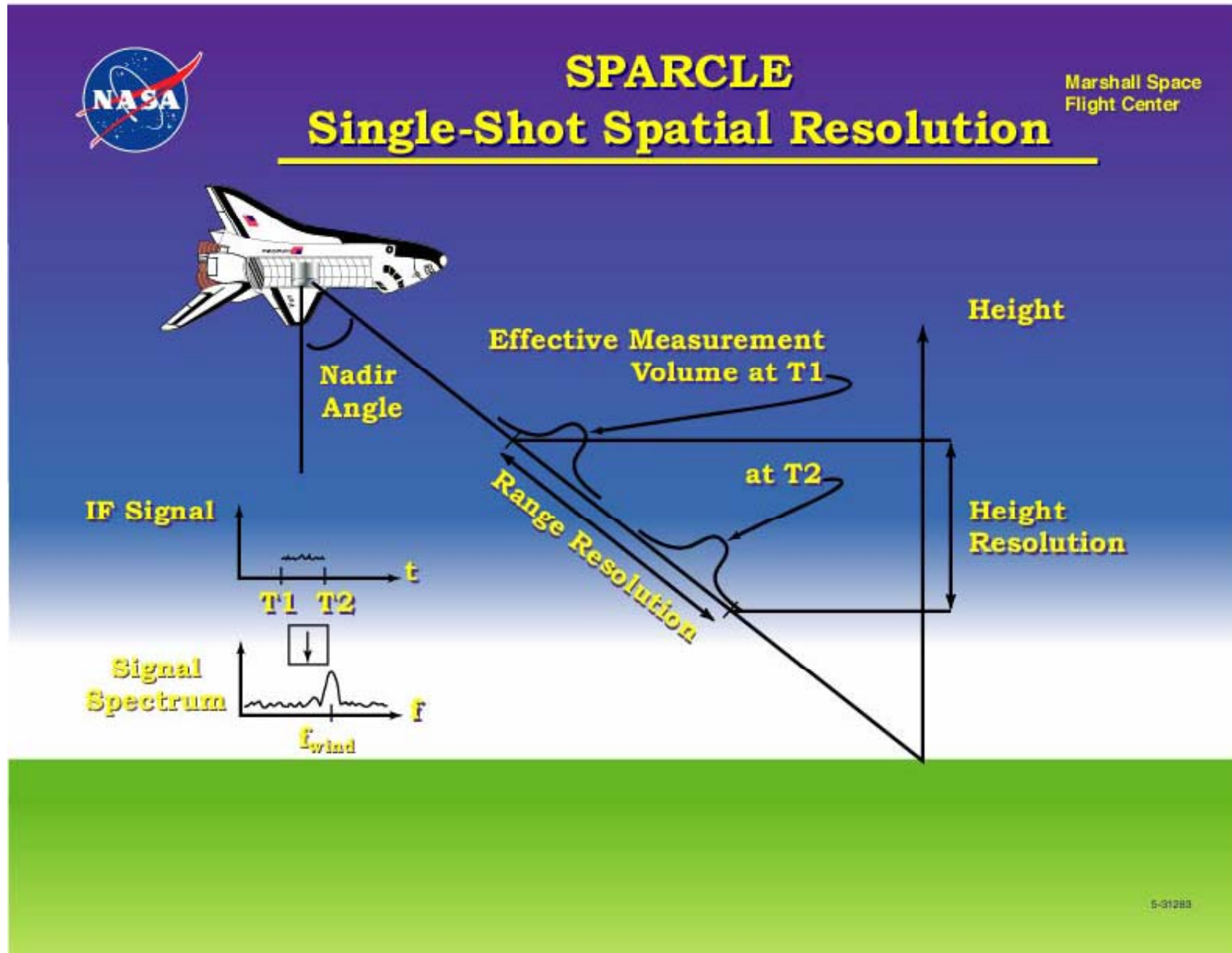
## Benefits Of The LO Laser

- High accuracy
- High photon efficiency
- No intensity measurements needed

*“heterodyne detection can allow measurement of the phase of a single-frequency wave to a precision limited only by the uncertainty principle”*

Michael A. Johnson and Charles H. Townes  
Optics Communications 179, 183 (2000)

# Range and Height Resolution





# 1 $\mu$ s (150m) Of Lidar Data And Its Spectrum

$V=10.00$  m/s  $M_s=8192$   $M=1600$   $MT_s=0.200E-05$  s

$\Phi=20$   $\Omega=2.0$   $w=0.100E+07$  Hz  $w_v=1.00$  m/s

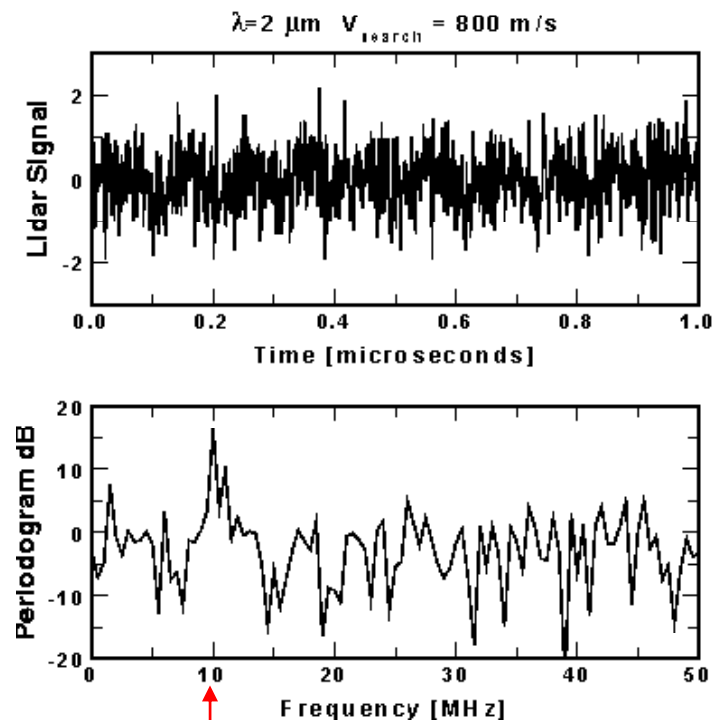
SNR=-19.031 dB SNR=0.01250 Bandwidth=800.0 MHz

$V=10.00$  m/s  $M_s=8192$   $M=1600$   $MT_s=0.200E-05$  s

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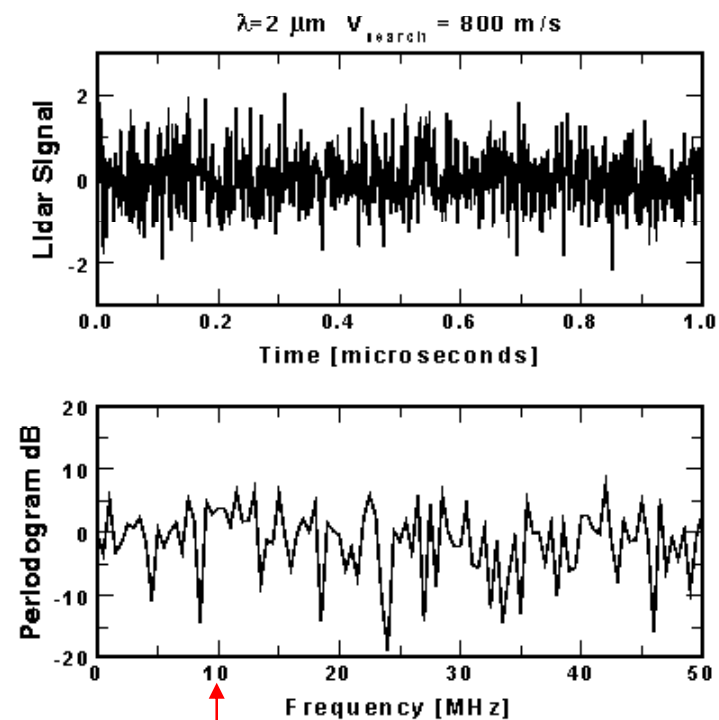
SNR=-19.031 dB SNR=0.01250 Bandwidth=800.0 MHz

## “Good” Wind Estimate



True wind, frequency = 10 m/s, 10 MHz

## “Bad” Wind Estimate





# Effect Of SNR On Velocity Estimation

Rod Frehlich, Stephen Hannon, Sammy Henderson

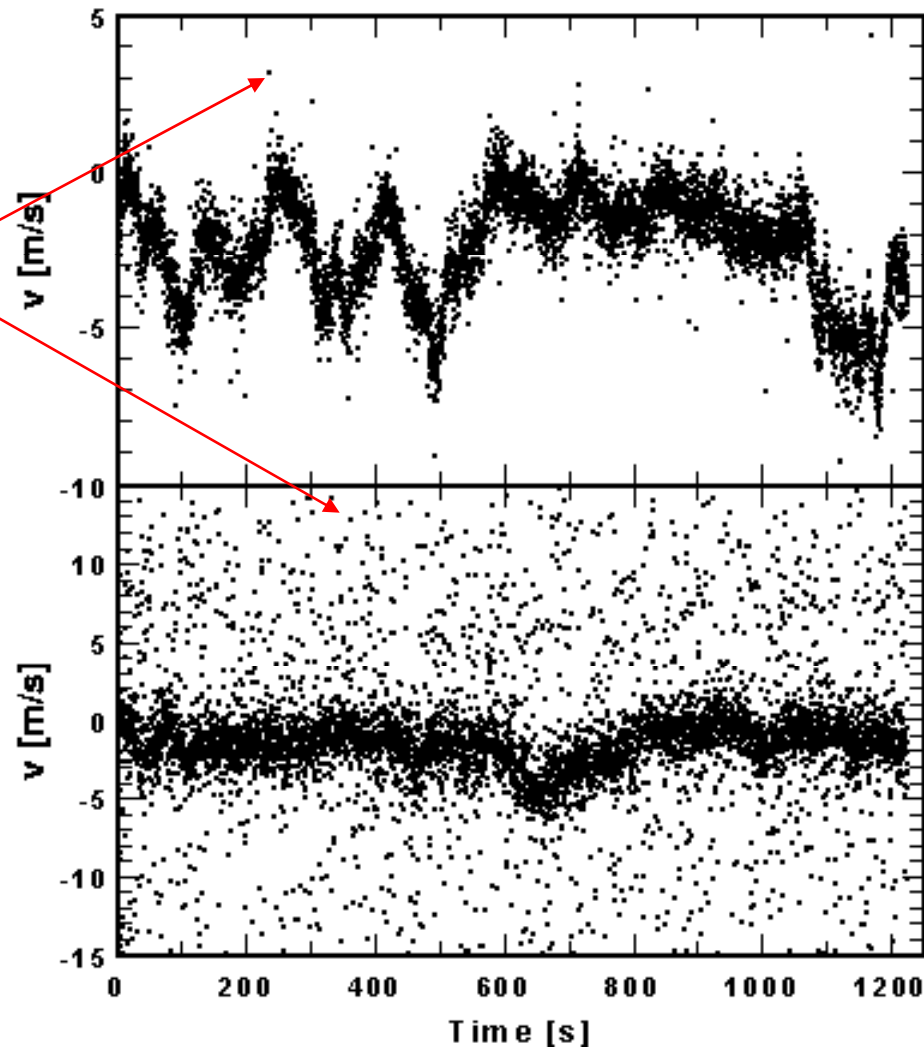
J. Atmos. Oceanic. Tech. Vol. 11, 1517-1528, (1994)

Actual lidar data  
6000 shots at 4.9 Hz

Top = Figure 4,  $R = 1$  km,  
high SNR

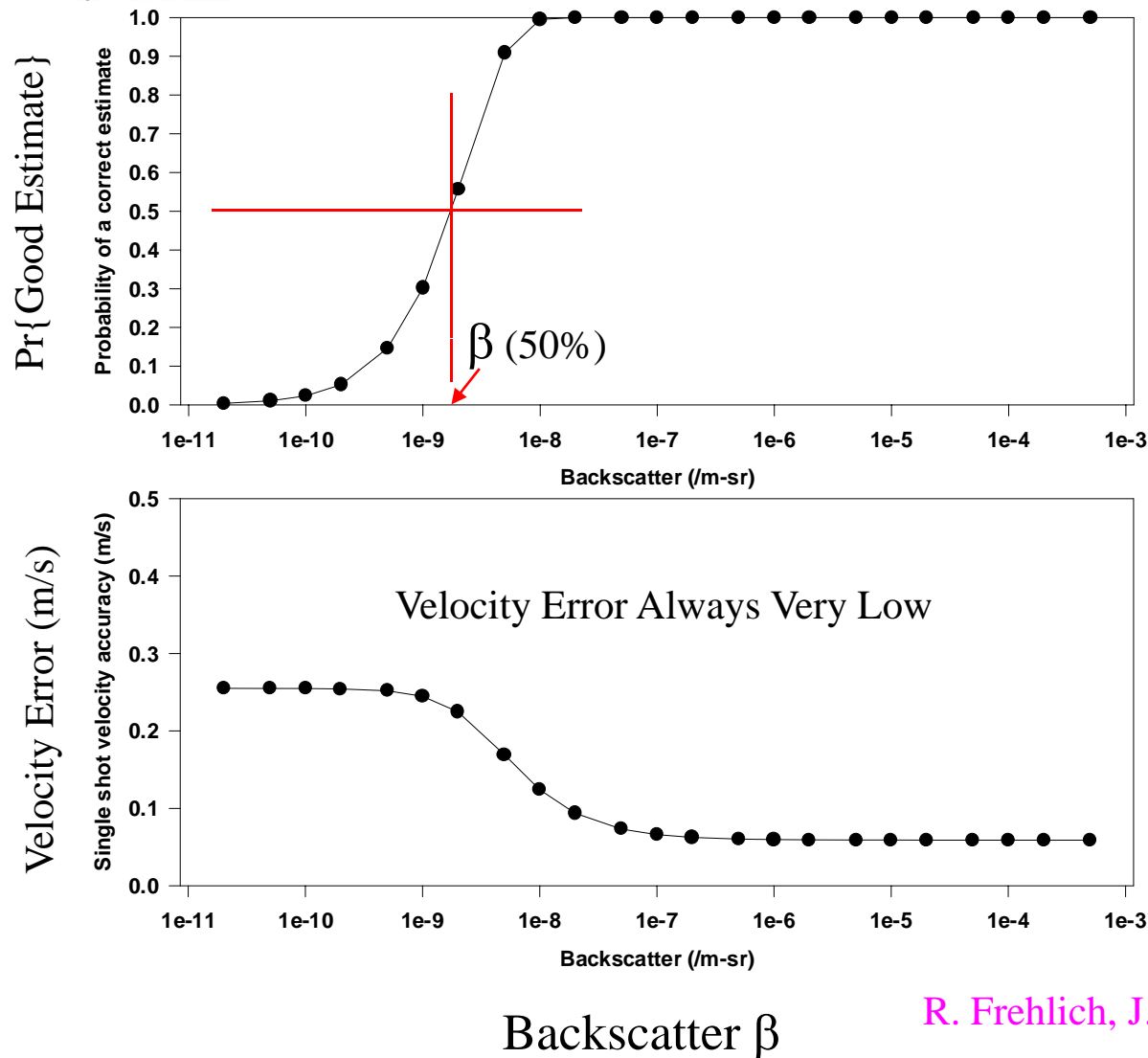
Bottom = Figure 5,  $R = 5$  km,  
low SNR

Unsuccessful  
or “bad” wind  
estimates;  
uniformly  
distributed  
over “allowed”  
velocity range





## Example of coherent lidar velocity estimator performance



Example plots are for a maximum likelihood estimator.

These curves 'slide' up and down the x-axis as a function of lidar design.

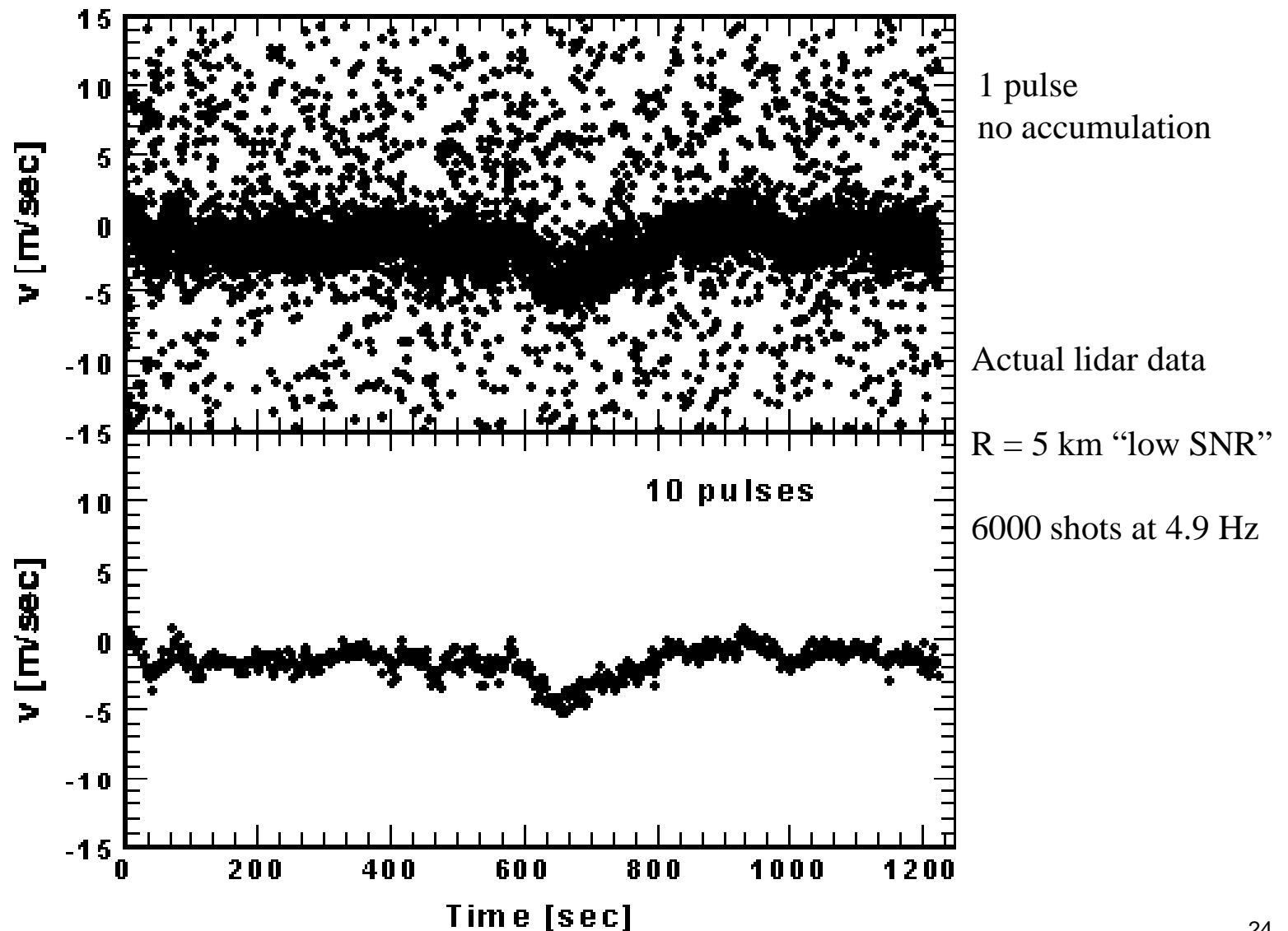
Maximum and minimum values and shape of each will vary with lidar parameters. However 'S' shape and the relationship between the two curves are characteristic of all advanced coherent lidar velocity estimators.

Theory and experiment agree to within 5%.

R. Frehlich, J. Atmos. & Oceanic Tech. 14, 54 (1997).



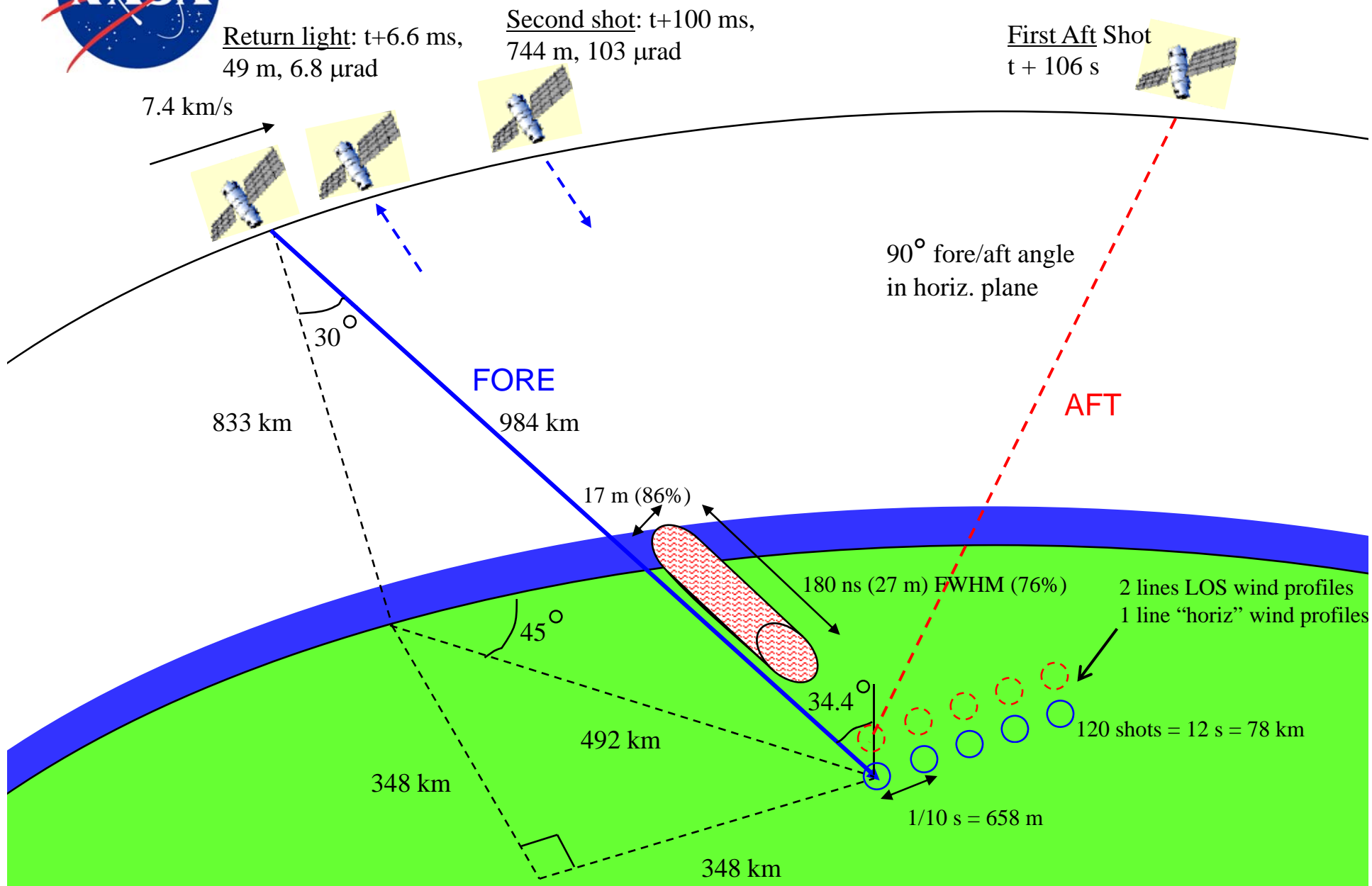
## Shot Accumulation Improves Velocity Estimation Trade Sensitivity For Time/Range/Resolution

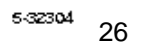






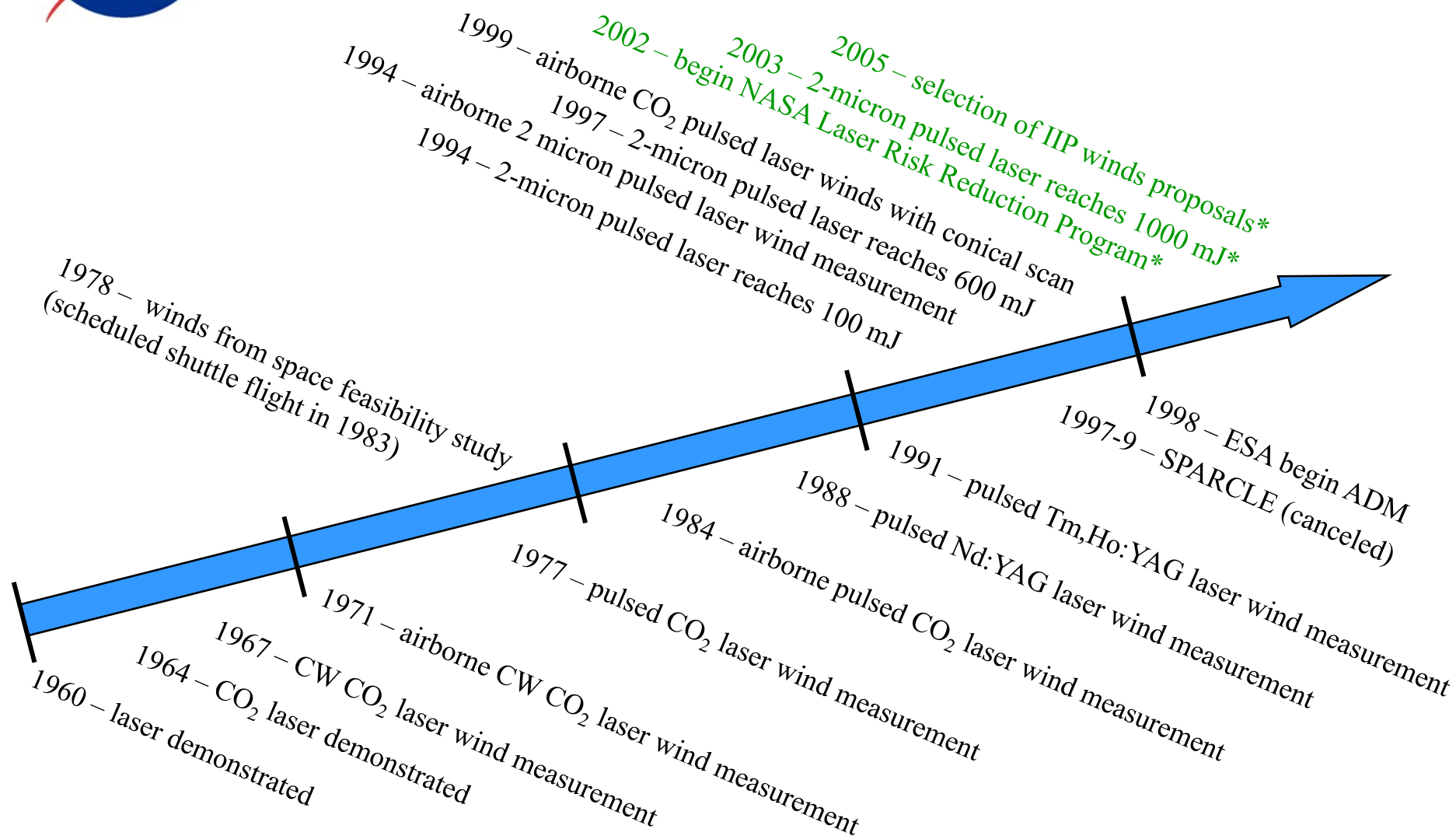
## Doppler Wind Lidar Measurement Geometry: 833 km







# Doppler Lidar Firsts Relevant to this IIP





# IIP Packaged Transceiver Requirements

Category	Requirement	Goal (if different) and/or Space Requirement	Reason
Laser Architecture	Master Oscillator Power Amplifier (MOPA)		High energy, beam quality, optical damage
Laser Material	Ho:Tm:LuLiF		High energy, high efficiency, atmospheric transmission
Nominal Wavelength	2.053472 microns		Atmospheric transmission
Pulse Energy	150 mJ	250 (space)	Computer modeling of measurement performance
Pulse Repetition Frequency	10 Hz	10-20 (space)	Shot accumulation, optimum laser diode array lifetime
Pulse Beam Quality	< 1.4 x diffraction limit		Heterodyne detection efficiency influence
Pulse Spectrum	Single Frequency	Few MHz (space)	Frequency estimation process
Injection seeding success	95%	99%	Shot accumulation
Laser Heat Removal	Partial Conductively Cooled	FCC (space)	No liquid lines in space
Packaging	Compact, engineered	Aircraft ready Space qual. (space)	As ready as possible for aircraft follow on



# Laser Design Considerations

- Laser wavelength
- Laser material
- Laser pumping geometry
- Laser cavity design
- Laser architecture



# Why Ho:Tm:LuLiF

- Why Ho laser?
  - Tm lasers in 2- $\mu\text{m}$  region have such a low gain cross-section ( $\sigma_{\text{em}} \sim 10^{-20} \text{ cm}^2$ ) that efficient, high-energy laser amplification is impossible without the risk of laser crystal or associated optics damage.
  - Ho lasers have large enough stimulated emission cross-section ( $\sigma_{\text{em}} \sim 10^{-19} \text{ cm}^2$ ) for effective amplification to obtain high-energy.
- Why co-doped?
  - Takes advantage of diode pumping for Tm lasers
  - Takes advantage of the efficient Tm 1:2 relaxation energy transfer process
  - Takes advantage of the high emission cross-section of Ho laser



# Why Ho:Tm:LuLiF – Cont.

- Why fluoride?
  - Fluoride
    - Long upper laser level lifetime ~ 15 ms, store more energy
    - Low up-conversion loss
    - Higher emission cross-section
    - Naturally birefringent material, no depolarization loss
    - Negative  $dn/dT$  → weak thermal lensing
  - Garnet
    - Isotropic
    - Excellent thermo-mechanical properties
- Why Lutetium?
  - Lanthanide series ions
    - Lutetium, Yttrium, Gadolinium
  - Lutetium
    - Lutetium – larger crystal field
      - larger manifold stark splitting → Small thermal population of ground state



# Laser Architecture

## Master Oscillator Power Amplifier (MOPA)

- Energy requirement
  - Single oscillator can't produce required energy
- Beam quality
  - MOPA preserves the good beam quality
- Lifetime
  - Permits more derating of pump diodes
- Efficiency
  - Multiple pass amplifier improving the efficiency
- Optics Damage
  - Reducing intra-cavity fluence





# Cavity Configuration

- Linear Cavity
  - Standing waves
  - Simple
  - Round trip - pass gain medium twice
- Ring Cavity
  - Traveling waves
  - No spatial hole burning in the gain-> single mode
  - Long cavity needed to obtain narrow linewidth
  - Beneficial for injection seeding through output coupler



# Pumping configuration

- Pumping geometry
  - Side Pumping
    - » Power scaling
    - » Uniform pumping
  - End Pumping
    - » Easy thermal management
    - » Easy to mode match
    - » Higher pump density
- Single Longitudinal Mode
  - Interferometric mode selection
  - Monolithic design, short cavity
  - Injection seeding

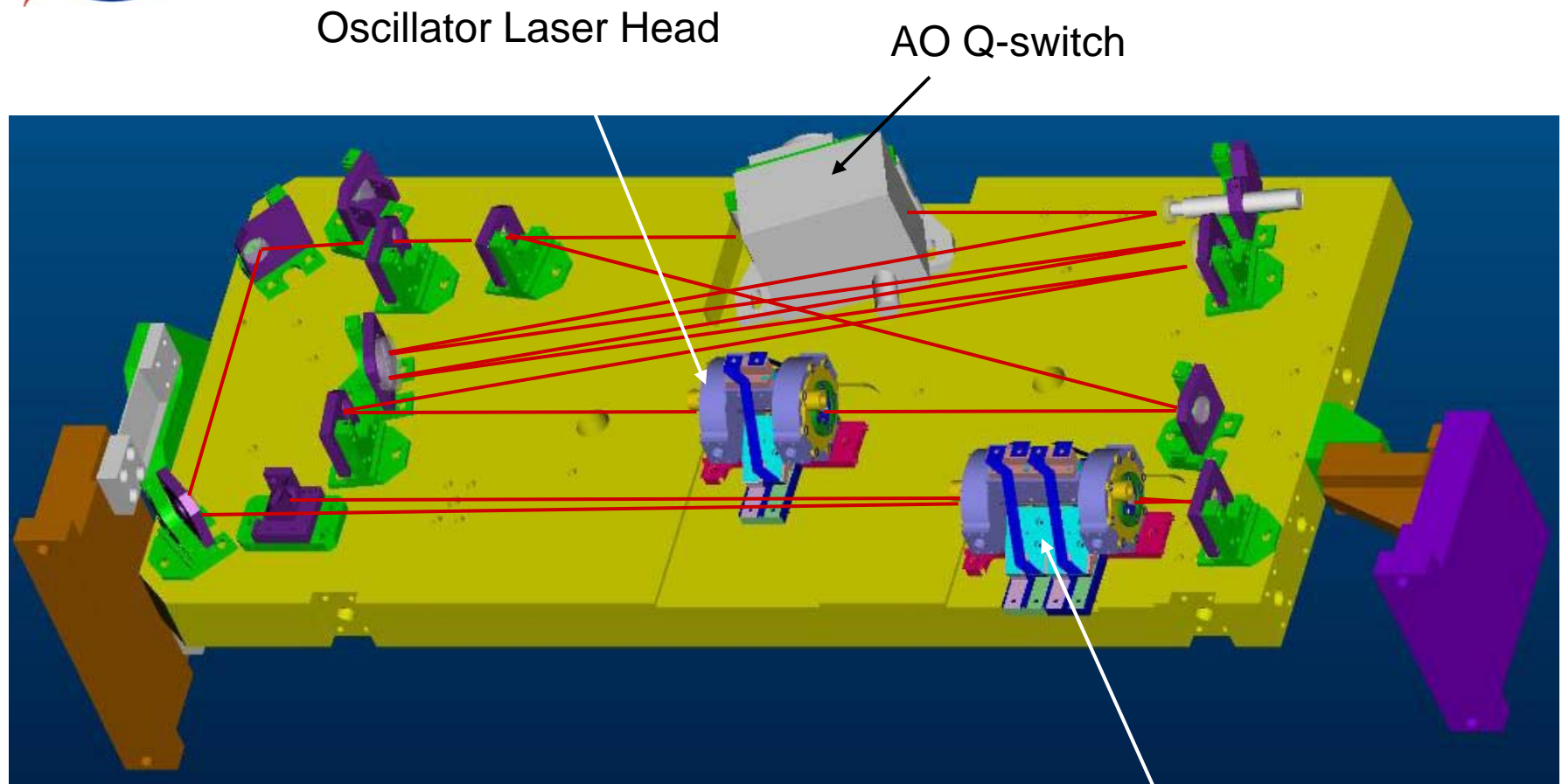


# Optical Bench

- Two options:
  - 26.5 x 23.0 x 7 inch single side
  - 26.5 x 11.5 x 7 inch double sided
- The split can be done such that the receiver optics and the seed laser on one side, and the power Oscillator amplifier on the other.
- Optical bench is water cooled, enclosed and dry purged.



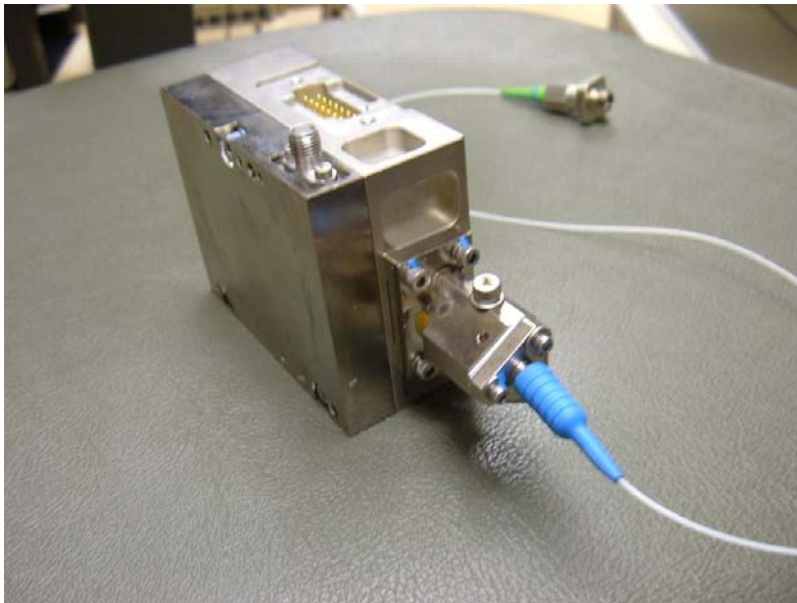
## LRRP Pulsed, 2-Micron Laser Transmitter Opto-Mechanical Design



- 3-m, bow-tie, unidirectional master oscillator power amplifier
- Seeding and receiver optics on reverse side
- Expect this hardware in about 8 weeks for LRRP



# Seed Laser



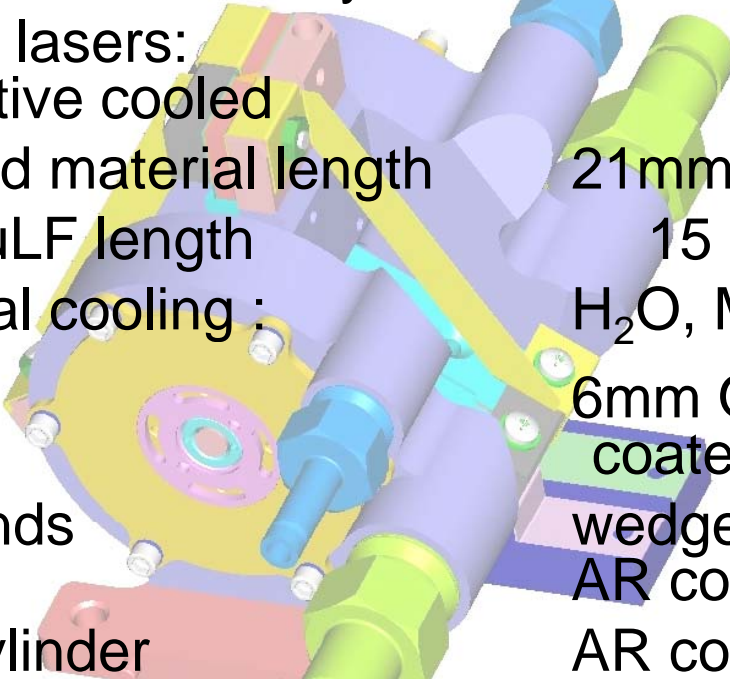
CW seed laser



Seed laser driver



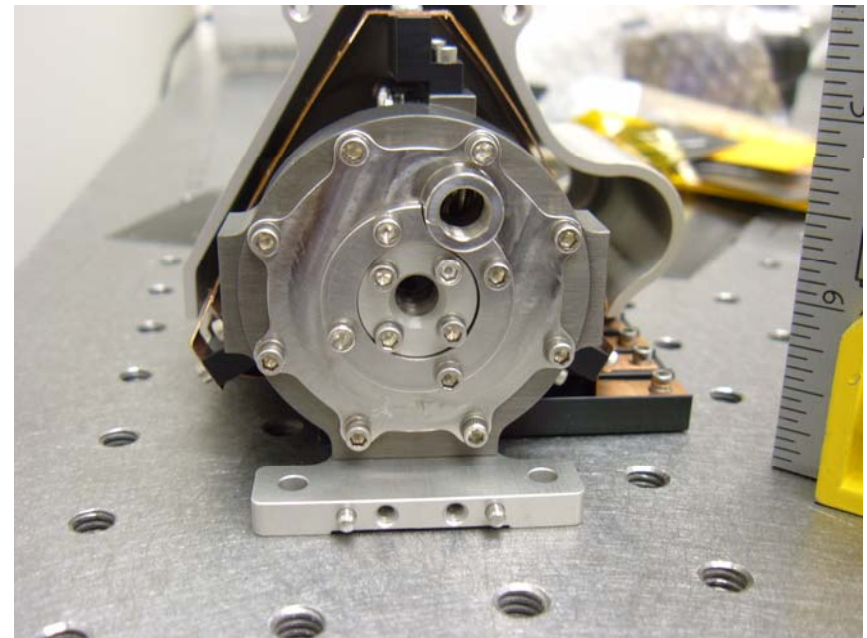
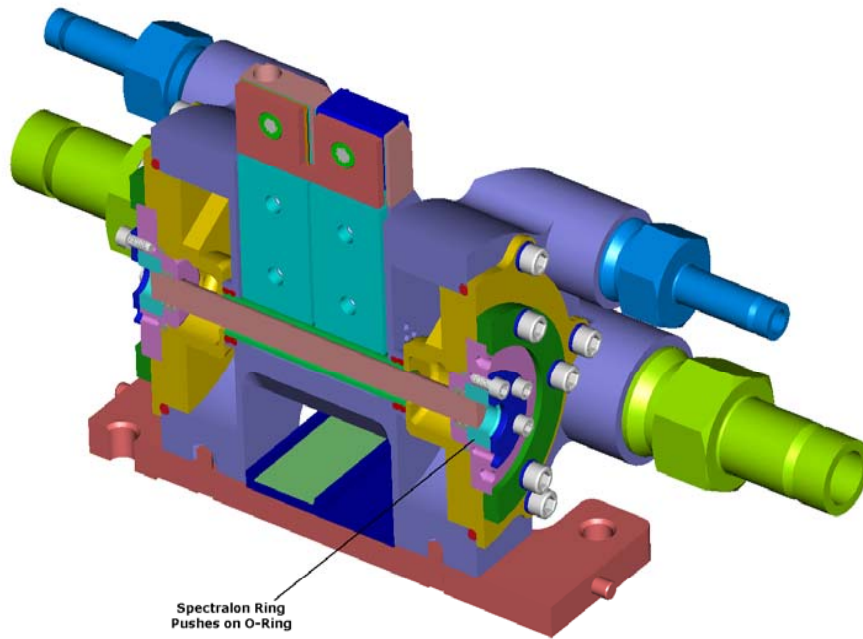
# Oscillator features

- Injection seeded
  - Cavity length
  - Output coupler Reflectivity
  - Diode pump lasers:  
conductive cooled
  - crystal doped material length
  - undoped LuLF length
  - Laser crystal cooling :
  - Tube size:
  - Laser rod ends
  - Laser rod cylinder
- >3m Ring  
~70%  
36 bars 100W/b  
21mm  
15 mm  
H<sub>2</sub>O, Methanol  
6mm OD 5mm ID AR  
coated for 792nm  
wedged 0.5° along c-axis  
AR coated for 2.053μm  
AR coated for 792nm
- 
- A 3D CAD model of a laser oscillator assembly. The model shows a central cylindrical component (laser rod) surrounded by various mounting and cooling structures. The components are color-coded: purple for the main body, yellow for the base, blue for the top, and green for the cooling structures. The model is shown from a perspective view, highlighting the complex geometry and assembly of the device.





# Oscillator Head





# Oscillator cavity length

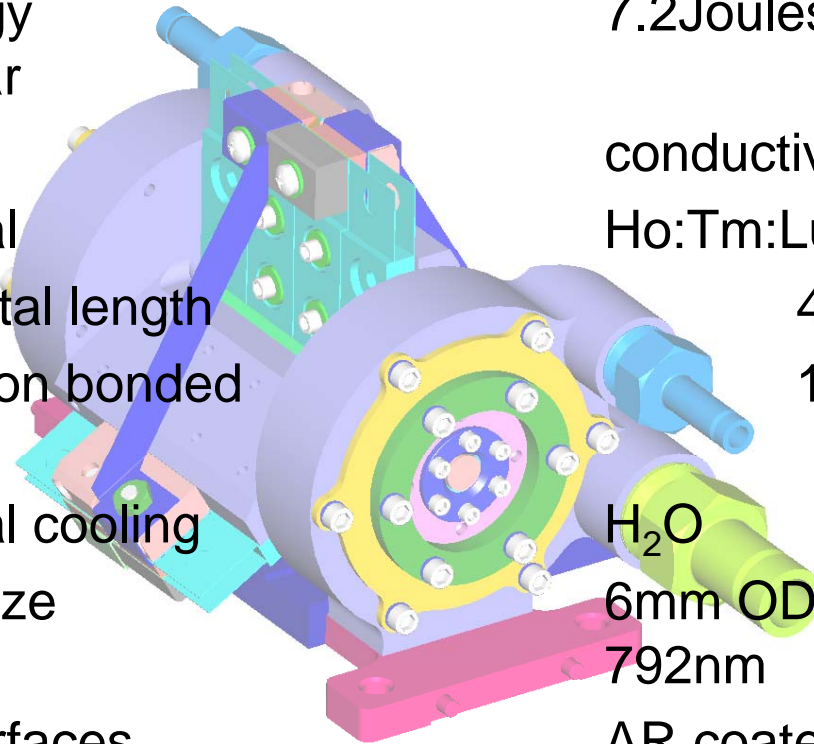
- Long cavity length is needed to obtain narrow linewidth
  - Pulse length is one of the critical parameters of a coherent Lidar.
  - A short pulse compromises frequency resolution while a long pulse compromises range resolution.
  - To meet the pulse length requirement, the oscillator length was changed from 2m to 3m. It prolongs the pulse width to near 200ns
  - The resonator has six mirrors and 8 bounces.





# Amplifier features

- Pump energy  
100watts/bar
- Diode laser
- Laser crystal
- Doped Crystal length
- Ends diffusion bonded  
crystals
- Laser crystal cooling
- Flow tube size
- Rod end surfaces
- Laser cylinder
- Path configuration



7.2Joules 12x6 bar arrays with

conductive cooled 'AA' Pkg

Ho:Tm:LuLF 0.5% Ho 6%Tm

41mm

15 mm undoped LuLF

H<sub>2</sub>O

6mm OD 5mm ID AR coated  
792nm

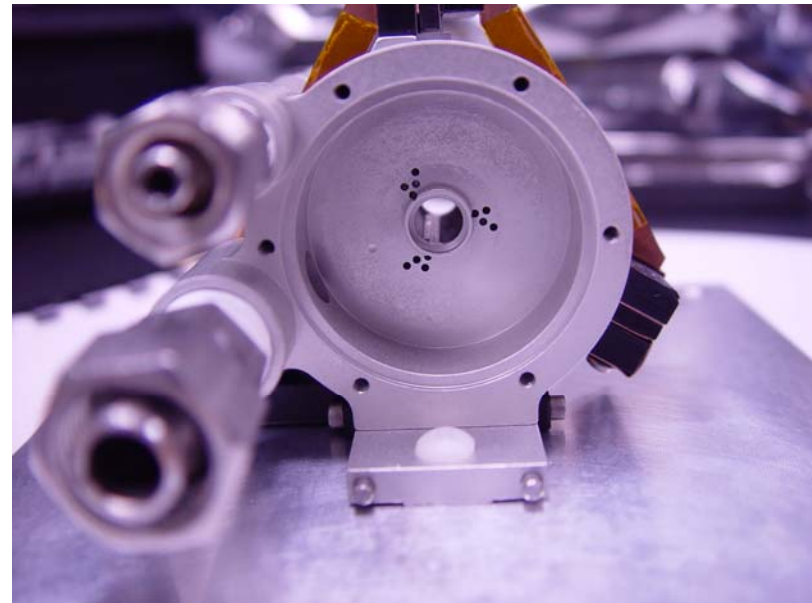
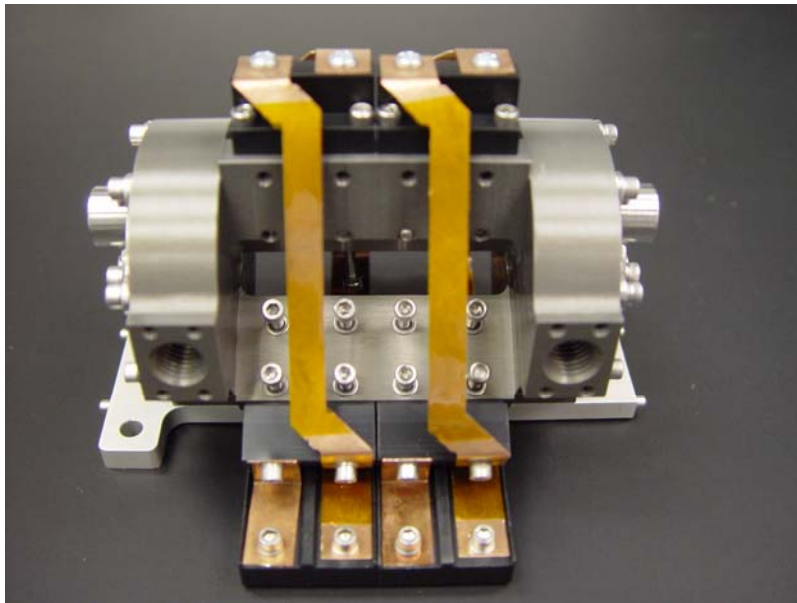
AR coated for 2.053 $\mu$ m

AR coated for 792nm

double pass



# Amplifier Module

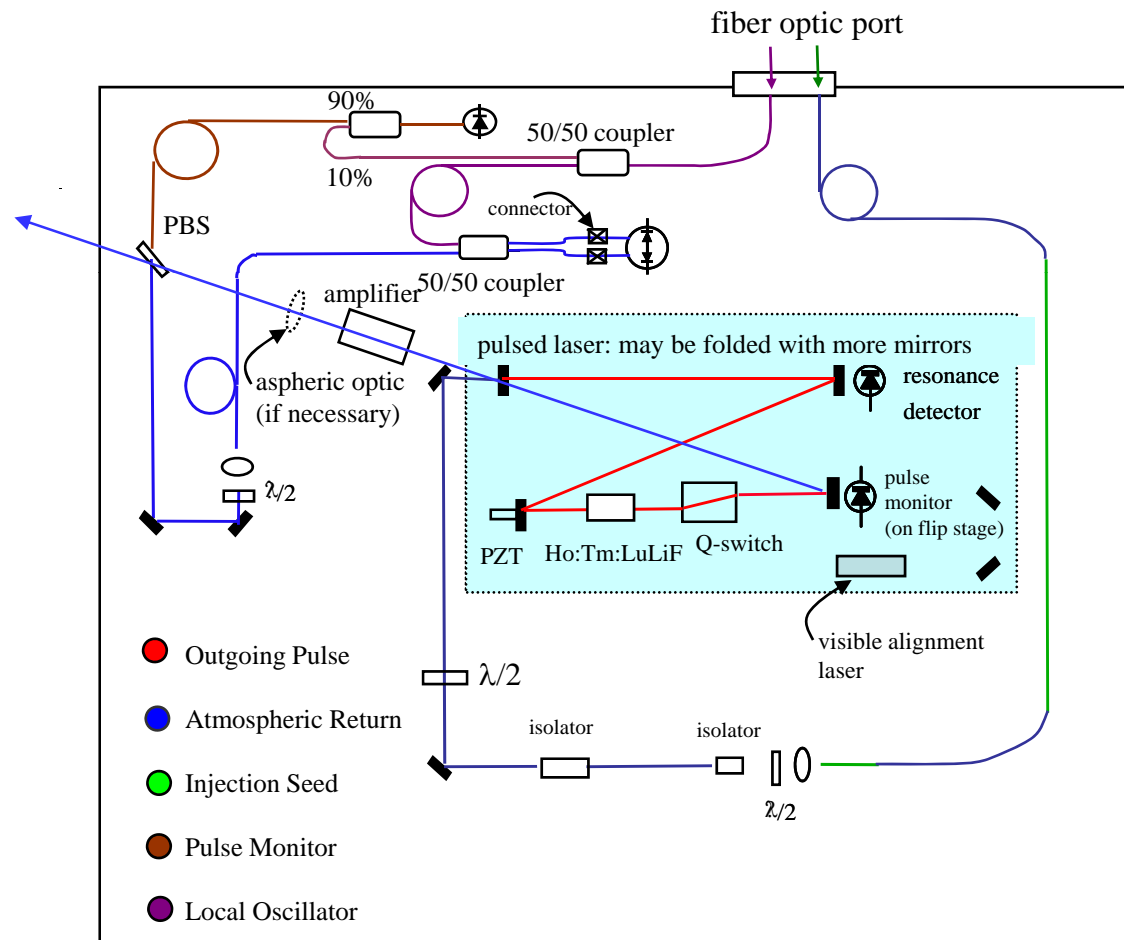




# Proposed Transceiver “Box”

- Modular approach with injection seed & local oscillator separate from transceiver.
- Separate seed/LO allows flexibility to adapt to 3 measurements scenarios:

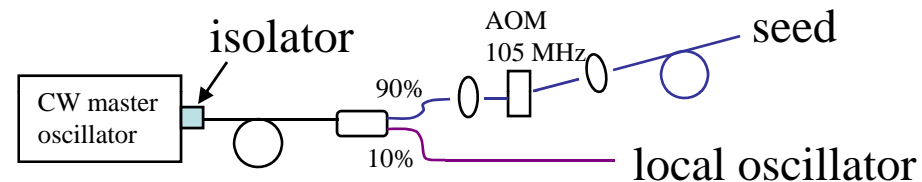
- simple, fixed frequency LO for ground or low platform speed.
- higher intermediate frequency for high platform speed
- swept LO for very high platform speed.
- DIAL of CO<sub>2</sub>



Note: only optical paths are represented; electrical and water paths are not shown.



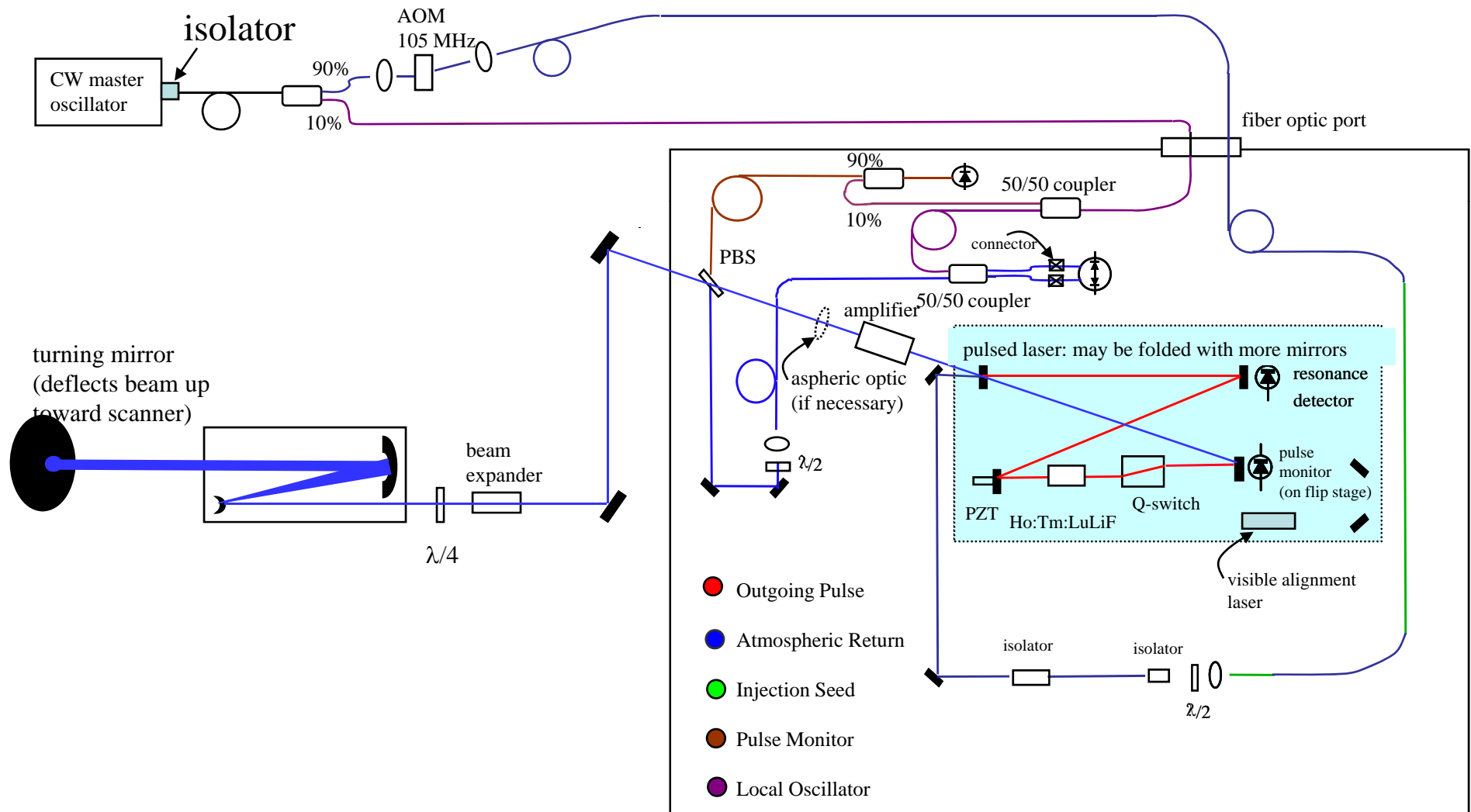
# Seed/LO Option 1



- baseline design for ground-based implementation.
- recommended for IIP demonstration.
- fiber-to-free space through AOM then back to fiber is disadvantageous—looking into fiber optic pigtailed AOM.
- could be packaged in rack-mount breadboard with fan for cooling (need thermal analysis).

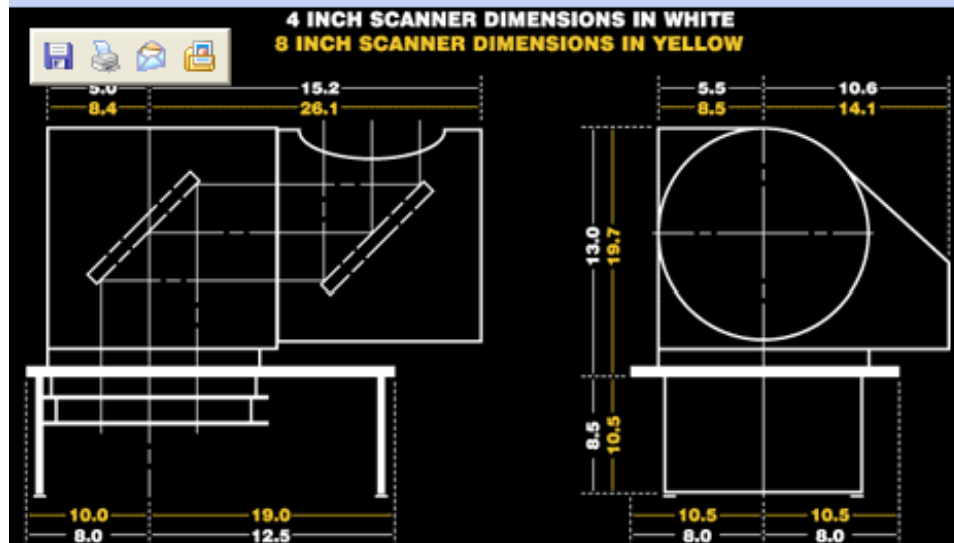


# Test Bed: Putting it all Together





# VALIDAR Scanner



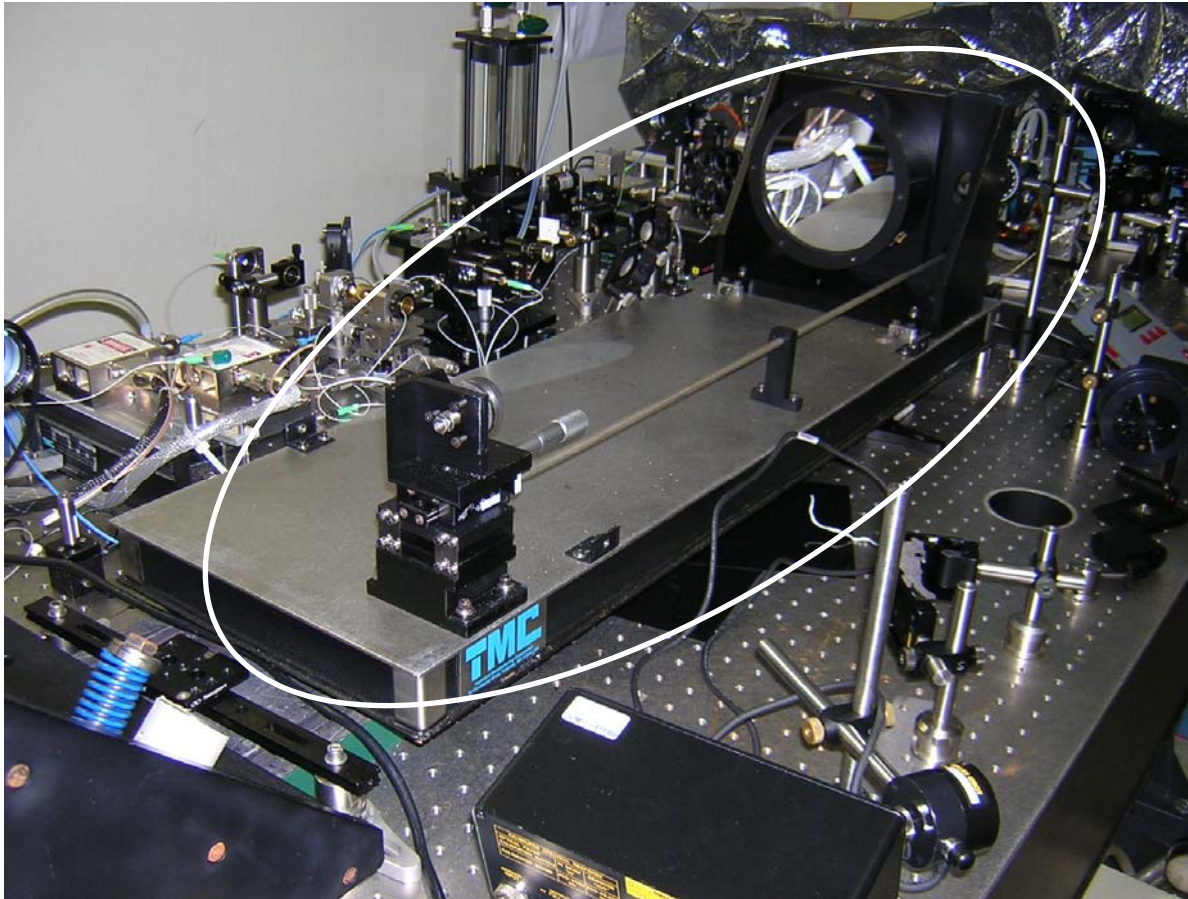
- scanner is mounted on roof of laboratory trailer.
- 8-inch clear aperture.
- can be pointed or scanned in elevation/azimuth for hemispherical coverage.
- linked to data acquisition computer for automated profiling of wind.







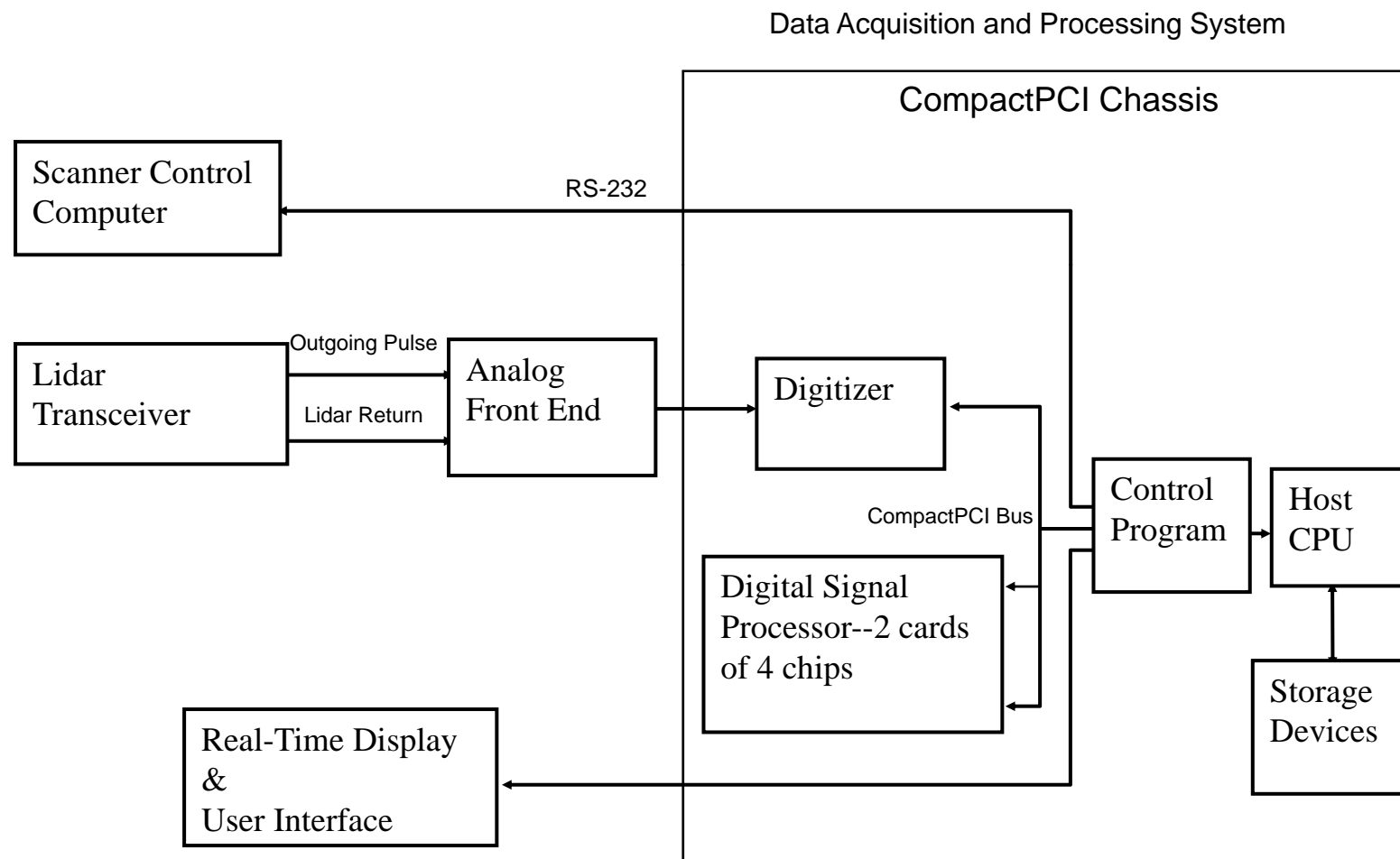
# VALIDAR Telescope



- off axis Dall-Kirkham design.
- 6-inch aperture
- 20X expansion



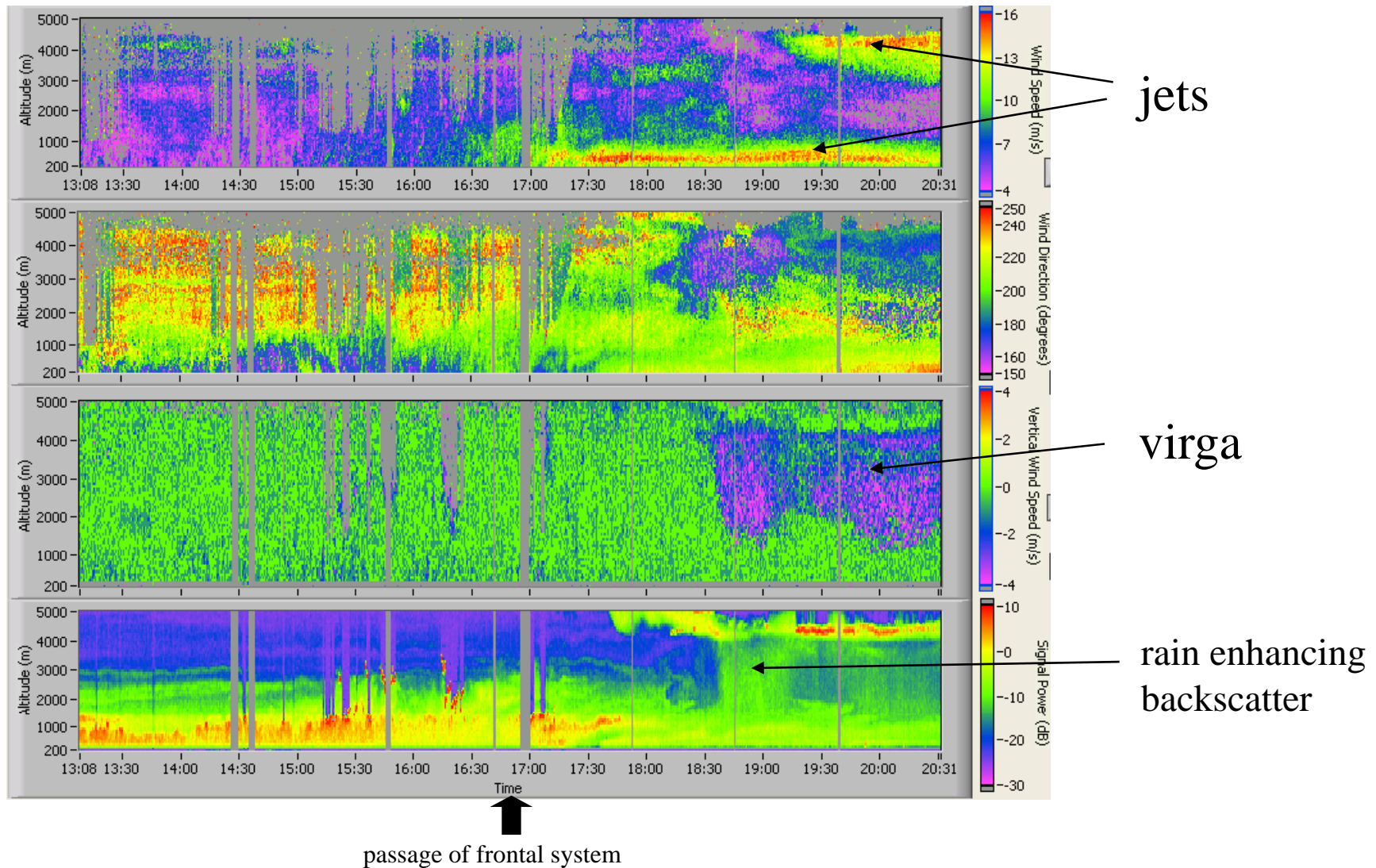
# Data Acquisition and Processing (already built)







# Atmospheric Measurements (will be better than this VALIDAR sample)





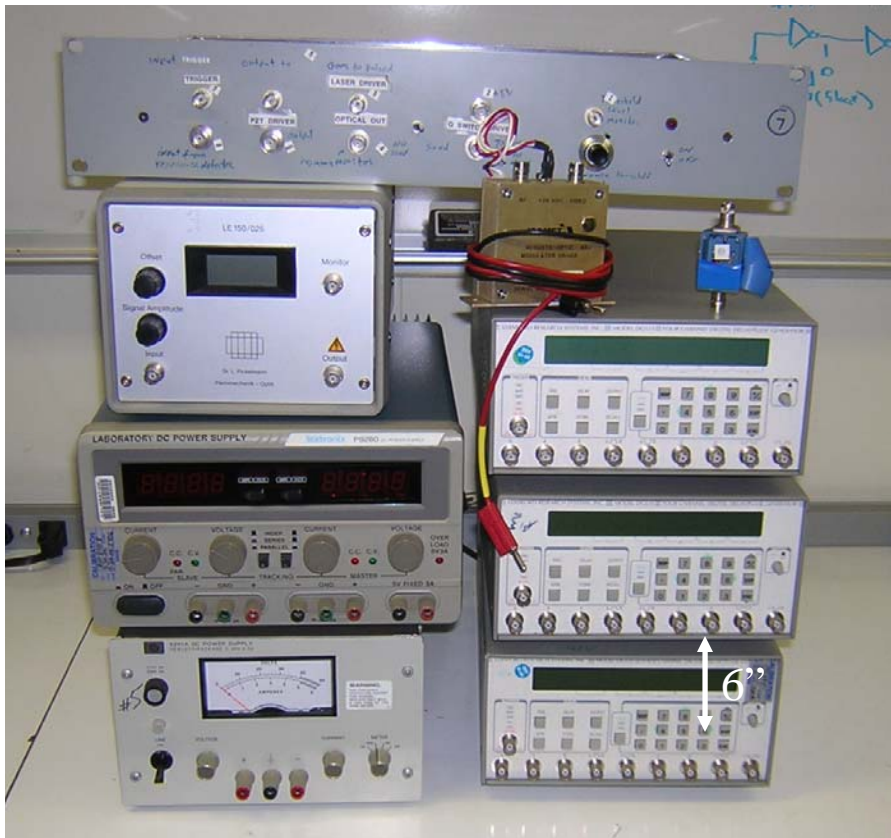
## Installation of Laser Timing Device

- The Laser Timing Device was installed in the VALIDAR system and tested in complete lidar.
- Significance of this new hardware:
  - Reduces size, weight, and complexity of control electronics associated with laser transmitter.
  - Improves performance of injection seeding and offers simpler adjustment of parameters.
  - Allows implementation of double-pulsing with injection seeding.
  - Graphical user interface.



# Simplification of Hardware

BEFORE



8 separate electronic boxes

AFTER



19" rack-mount enclosure, 1.75 inches high



# IIP Year 1 Financials

As of 6/8/06

	Budget	Committed	Obligated	Costed
FY05 Funds	\$175.0K	174.6K	115.9K	24.2K
FY06 Total	841.3K	317.4K	272.7K	111.3K
Labor*	189.5K	48.3K	48.3K	48.3K
G&A	189.0K	29.1K	29.1K	29.1K
Service Pools	160.6K	33.9K	33.9K	33.9K
Procurement	296.9K	206.2K	162.4K	0
Travel	5.3K	0	0	0

\*1.45 FTE  
plan  
0.57 FTE  
actual



# Summary

- IIP project 6 months into 36 month effort
- On schedule and budget to date
- Leveraging LRRP work on compact laser in 05 and 06
- Plan on significant steps of compact, engineered packaging of state-of-the-art laser/lidar technology. TRL definitions do not reveal significant progress.
- Companion IIP at GSFC for noncoherent Doppler wind lidar will complement this project to permit hybrid DWL on aircraft and then in space
- Project very consistent with findings of NASA/ESTO Laser/Lidar Technology Requirements Working Group results (FY06). To be issued in final report
- Anticipate strong endorsement of global winds by NAS decadal study on earth sciences
- Same technology promises additional applications for earth and Mars

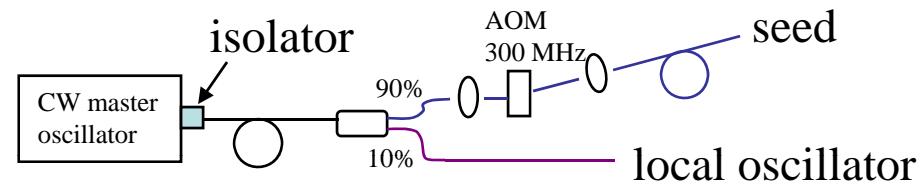


BACK UP





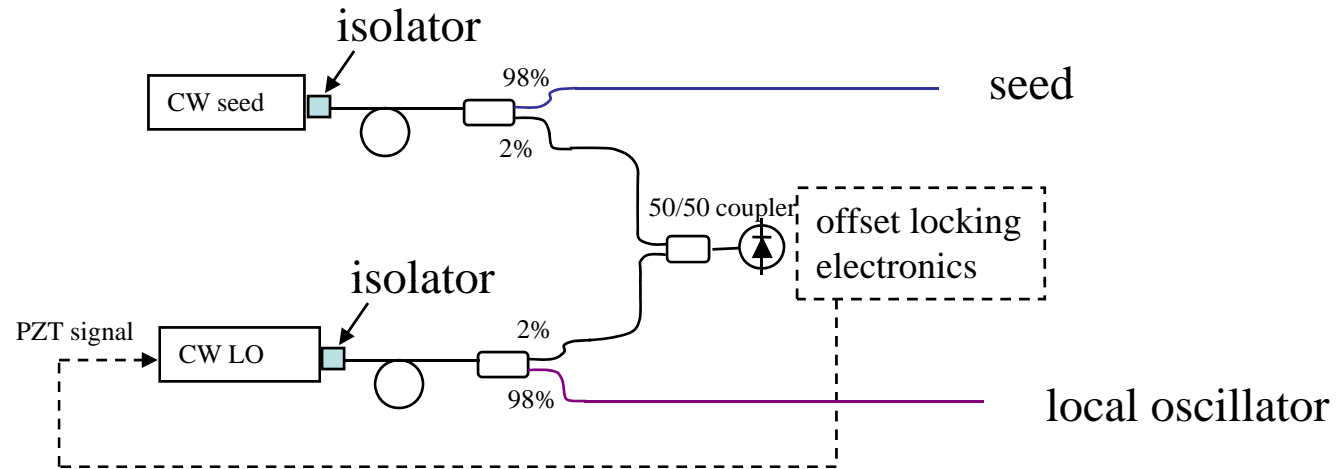
# Seed/LO Option 2



- used for aircraft.
- same as Option 1, except AOM offset is higher.
- system may require replacement of heterodyne photodetectors.
- aircraft speed and scanner angle are used to select a frequency to beat down heterodyne signal to bandwidth of data acquisition system.



# Seed/LO Option 3



- used with space mission with very high Doppler shifts from satellite motion. While IIP hardware would not be used for a space mission, useful system testing could be accomplished if this seed/LO option could be incorporated into system.





# Solid State 2-micron Lasers

- Tm Lasers (pump diodes 780-805nm)
  - YAG, YLF,  $\text{YAIO}_3$ ,  $\text{YVO}_4$
- Ho:Tm Lasers (pump diodes 780-805nm)
  - LuLF, YLF, GdLF, YAG,  $\text{YVO}_4$
- Tm pumped Ho lasers (pump diodes 780nm)
  - Tm solid state laser pumped Ho Laser
  - Tm fiber laser pumped Ho Laser
- Ho Lasers (pump diodes 1900nm)
  - YAG



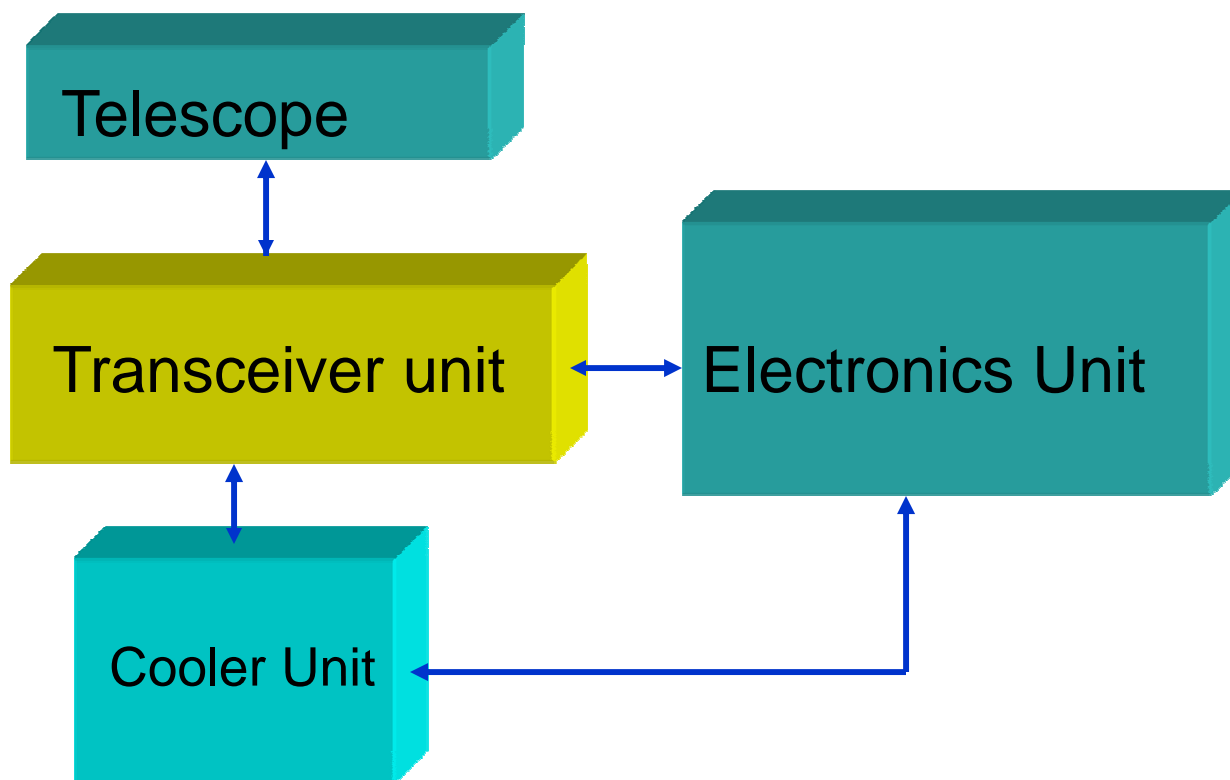
## Transceiver Environment Requirements

- Platform: ground-based (Airborne qualify-able)
- Operational Temperature 0°C -30°C
- Non-Operational Temperature -25° C; +50°C
- Operating Altitude Range Sea level to 30,000 ft
- Humidity <50% RH@25°C
- Vibration 2.0 g-rms
- Optical bench temperature controlled
- Coolant Temperature 5 °C
- Coolant Flow
  - Laser rod 0.4 GPM
  - Diode Laser 1.5 GPM
  - Bench 1.5 GPM
- Coolant Pressure 50 psi at 6 GPM

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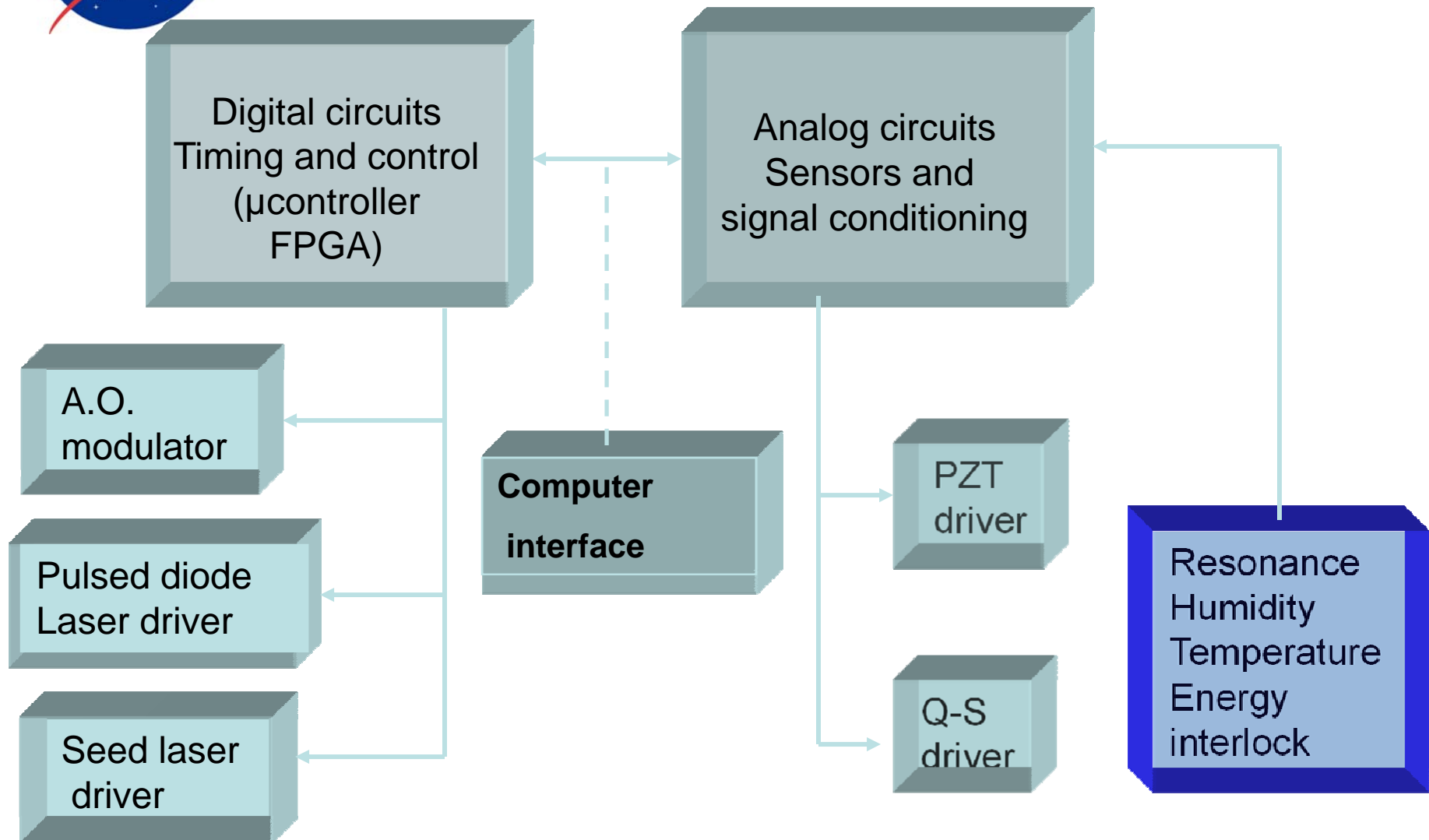


# Wind Lidar Block Diagram



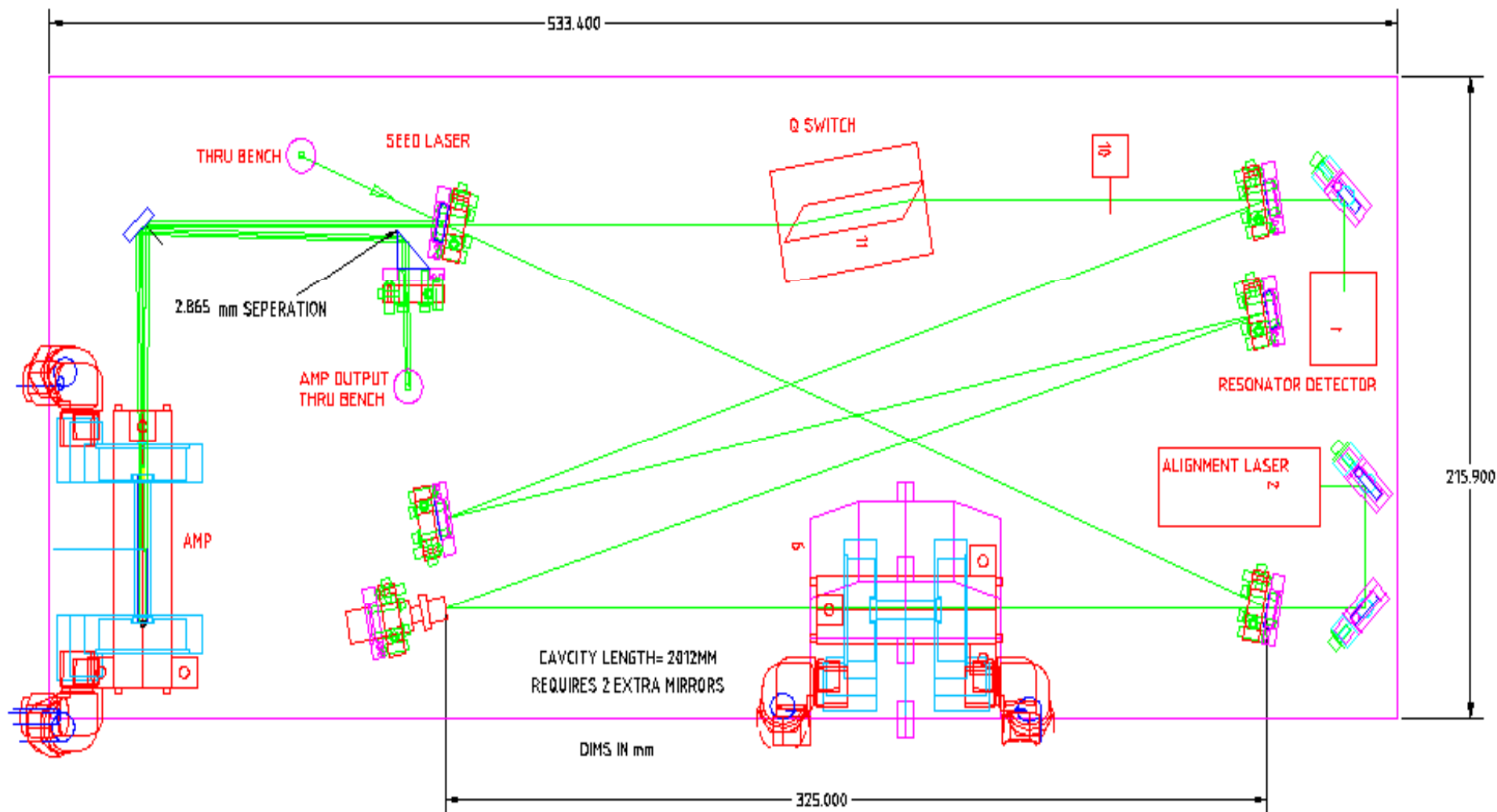


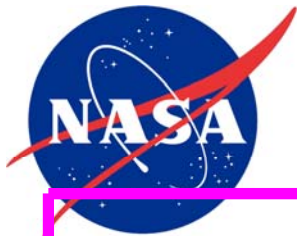
# Electronics Block Diagram



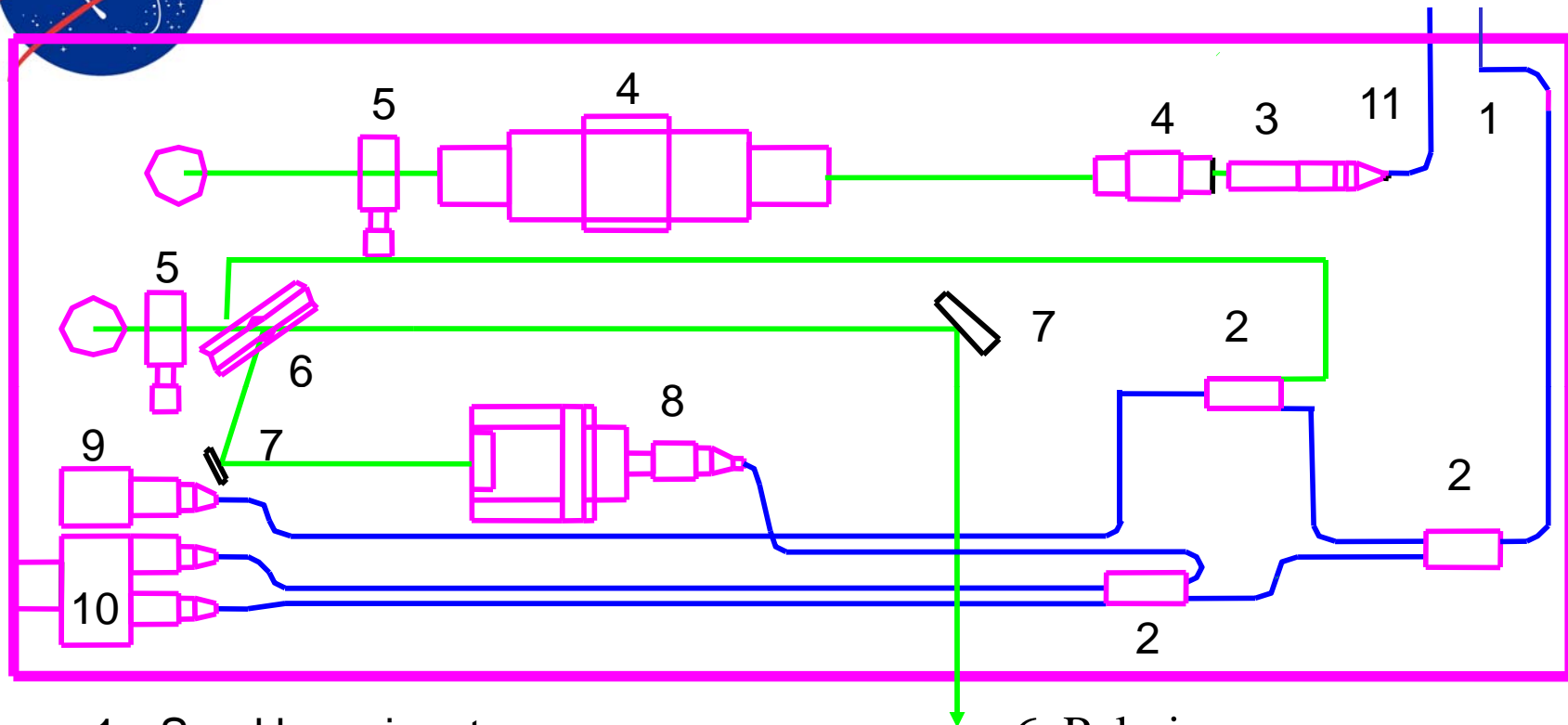


# Oscillator and Amplifier layout





# Receiver Optics layout

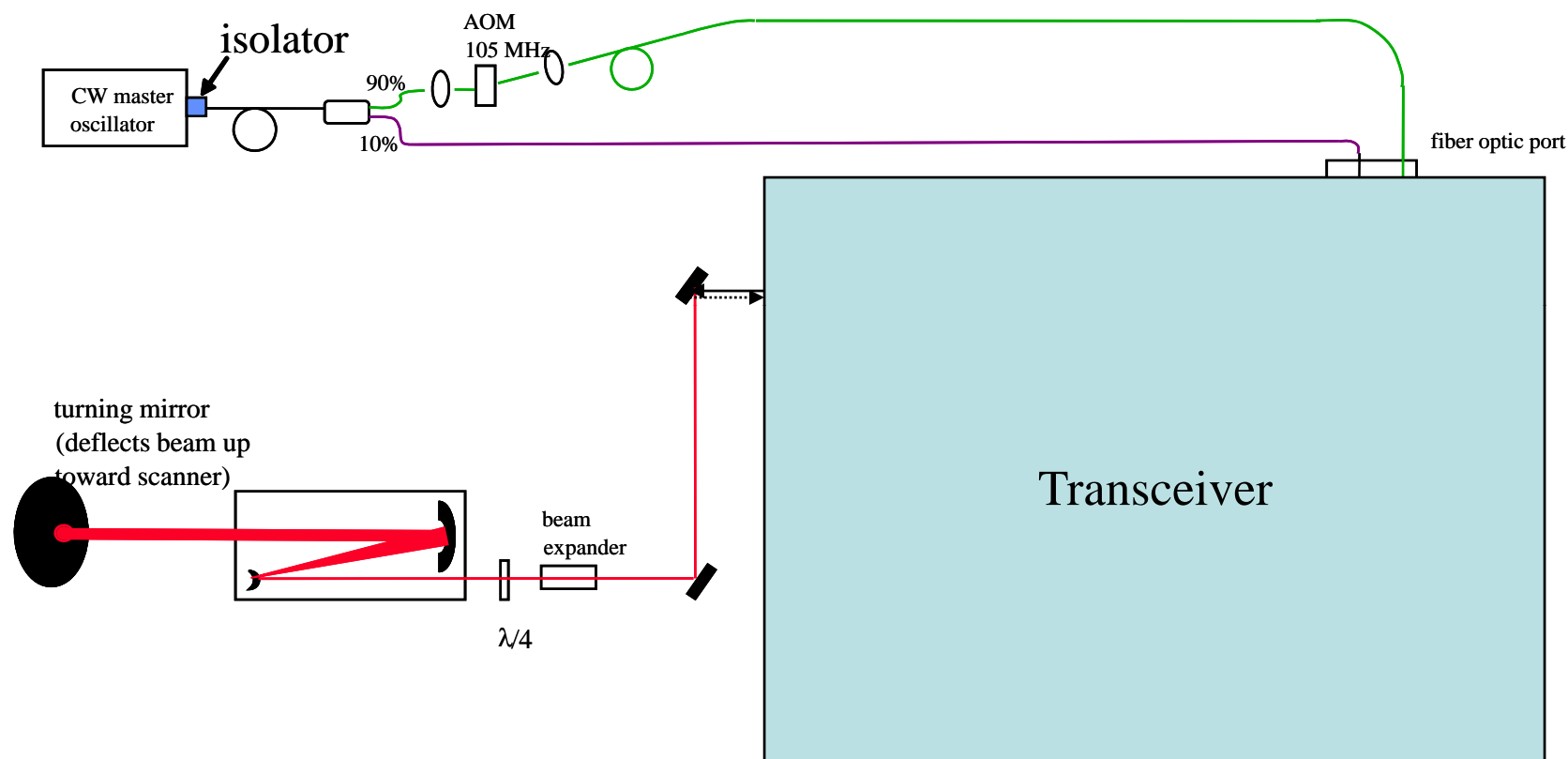


1. Seed laser input
2. Fiber beam splitter
3. Collimator
4. Faraday isolator
5.  $\frac{1}{2}$  wave plate

6. Polarizer
7. Beamsteering optics
8. Receiver signal optics
9. Heterodyne monitor
10. Receiver detectors
11. AOM output



# Transceiver integration with lidar





# Sensors

- Optical detectors:
  - Energy monitor (InGaAs or Pyroelectric)
  - Temporal pulse and energy monitor  
(Photo electro-magnetic detector )
  - Resonance detector (InGaAs )
  - Seeding quality (InGaAs )
  - Return signal (dual input InGaAs fiber coupled )
- Humidity sensors
- Temperature monitors



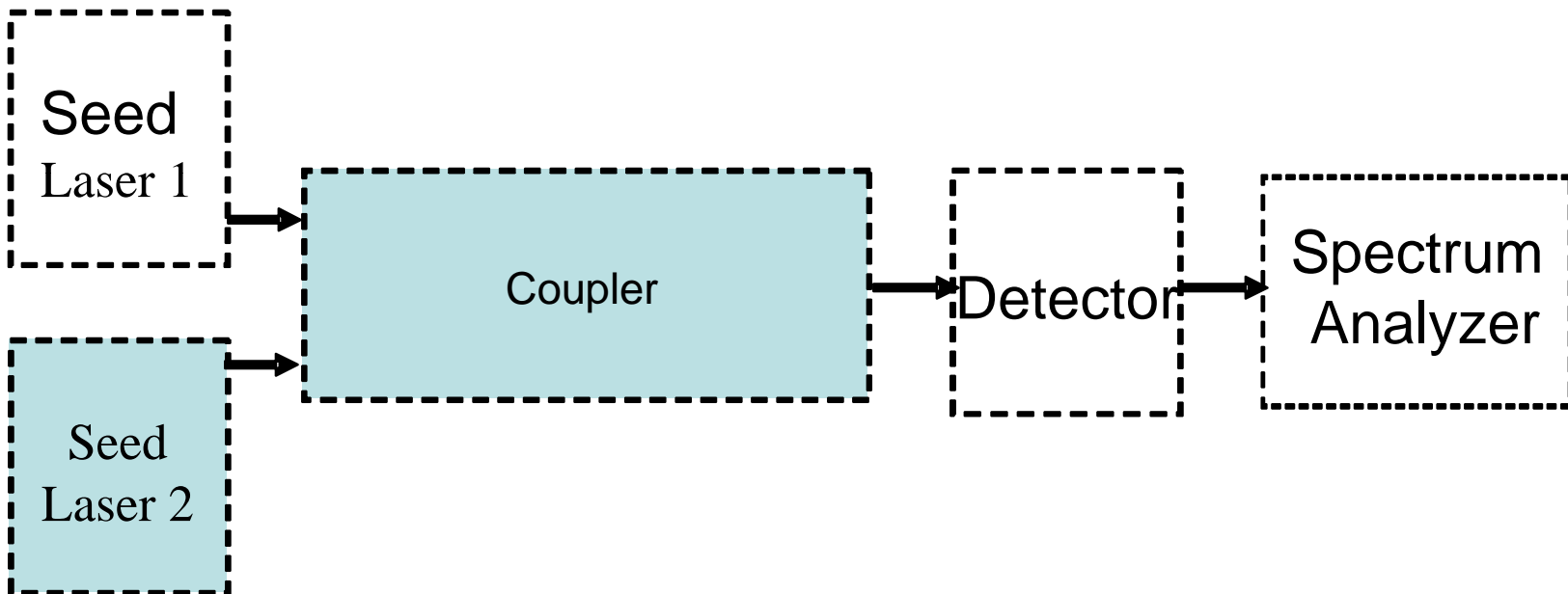


# Seed Laser

- Spatial mode TEM<sub>00</sub> Gaussian
- Output >35mw
- Output isolation: 60dB fiber coupled
- Additional protection: >50 dB between the oscillator and the AO modulator
- Fiber type single mode  
polarization preserving
- Fiber core diameter 6μm
- Operating conditions 20° to 25°C heat sink temperature

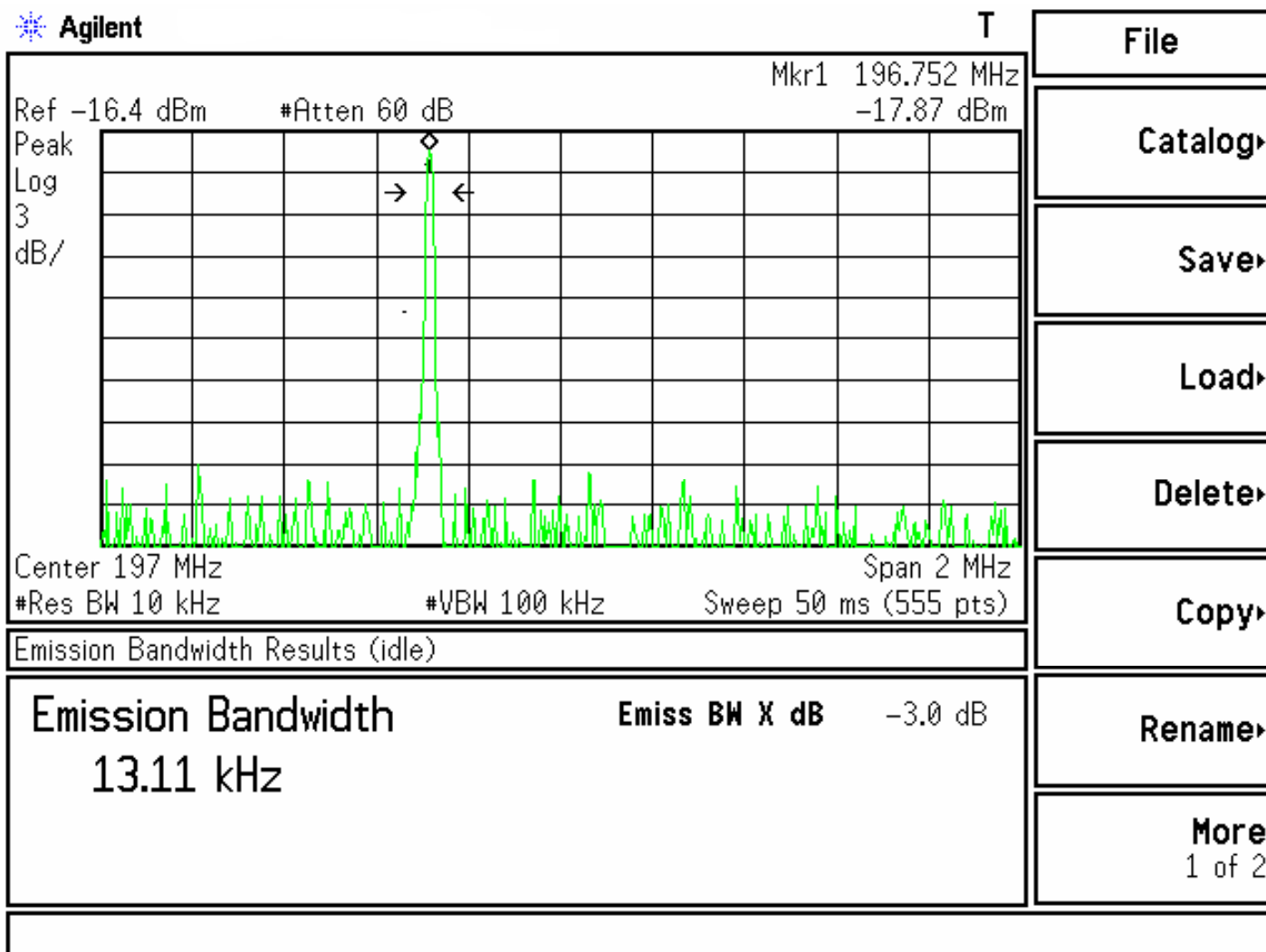


## Seed Laser Linewidth Measurement



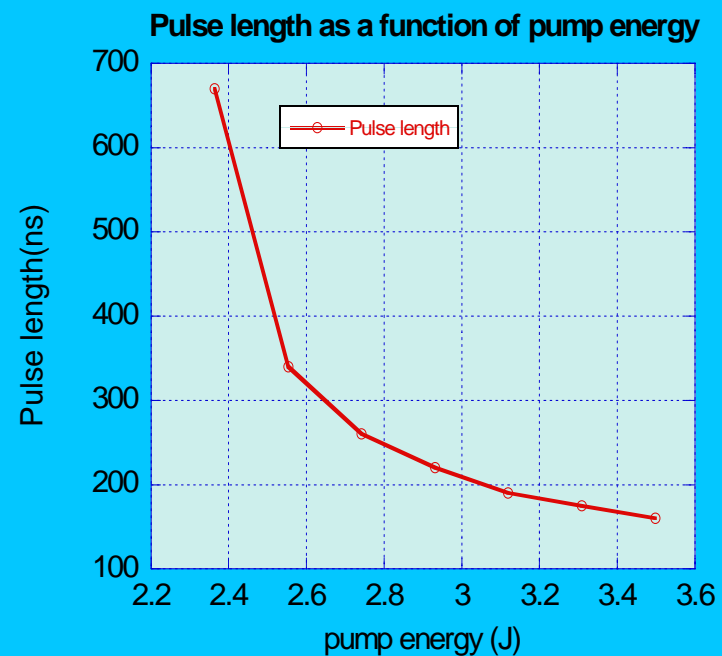
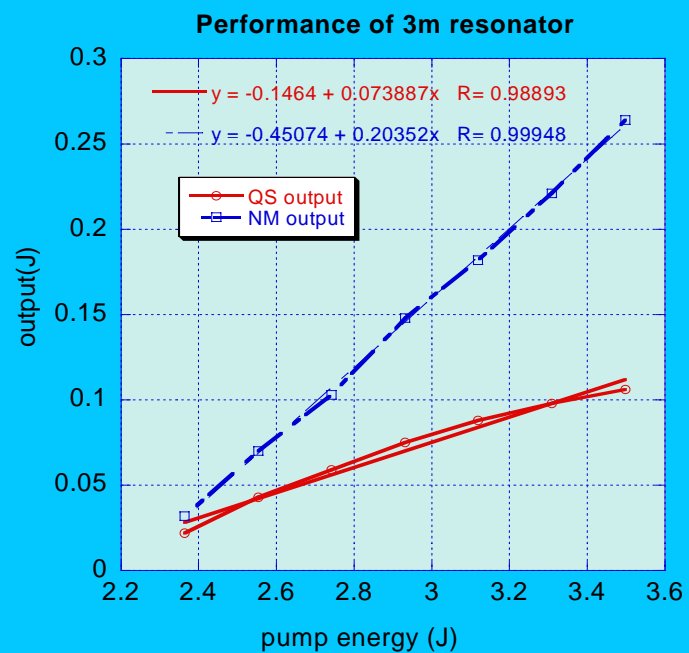


# Seed laser line width



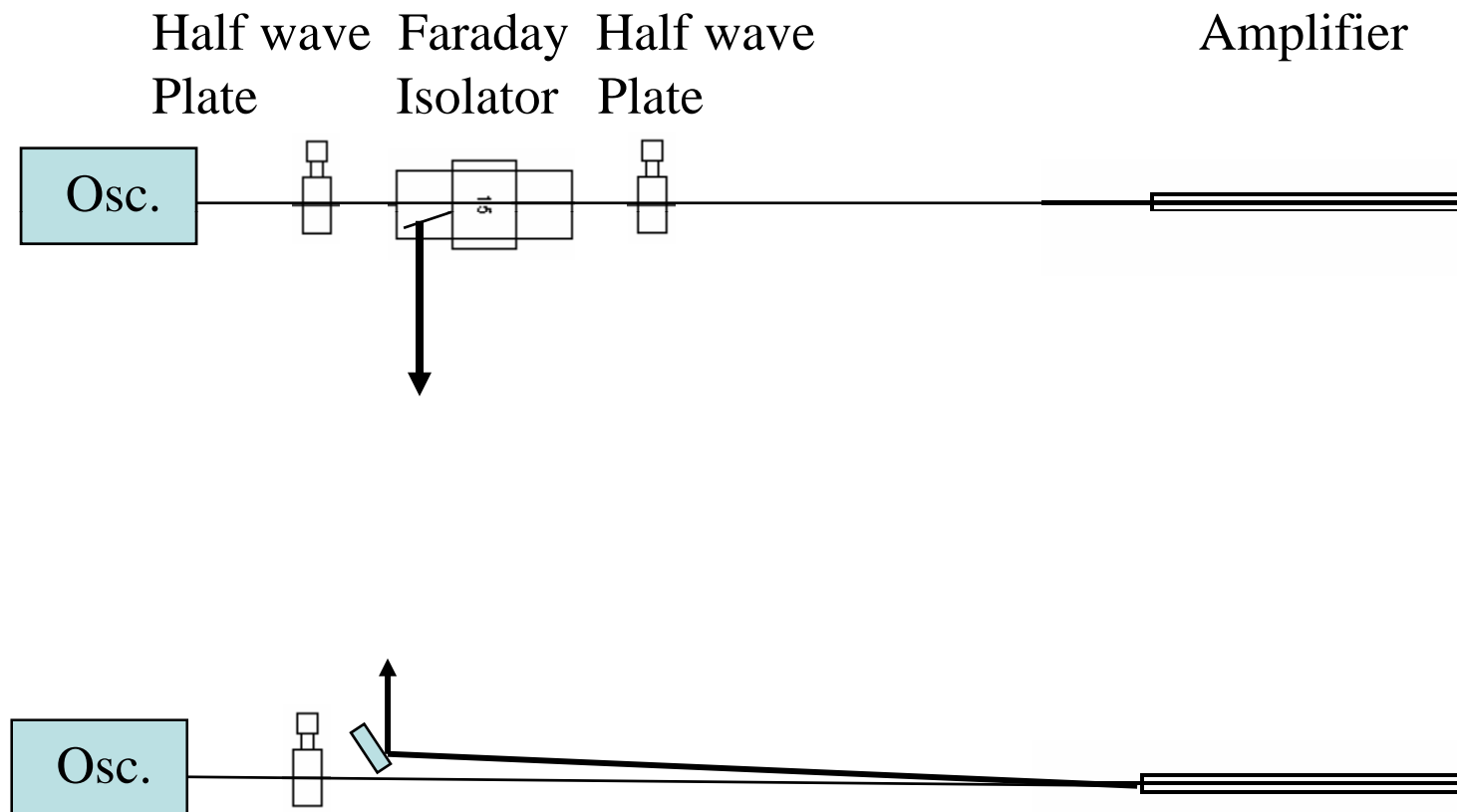


# 10Hz Oscillator performance



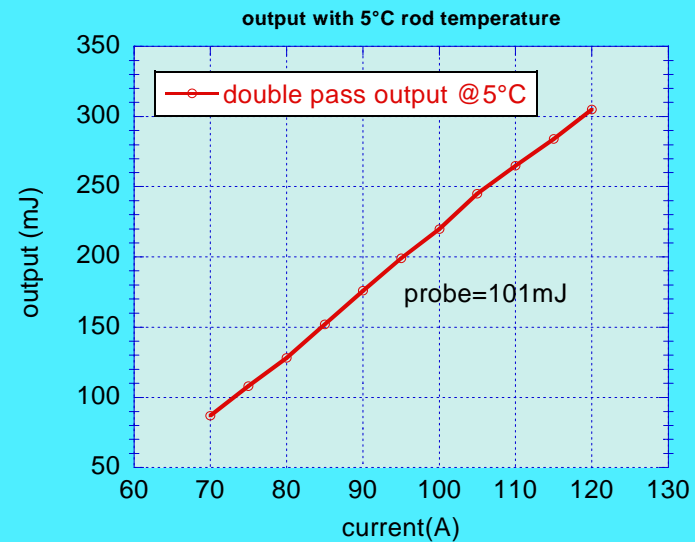
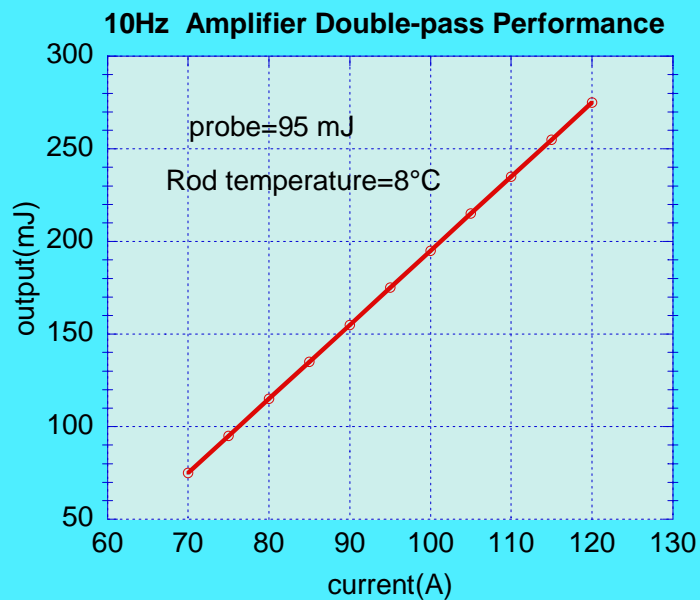


# Amplifier Architecture



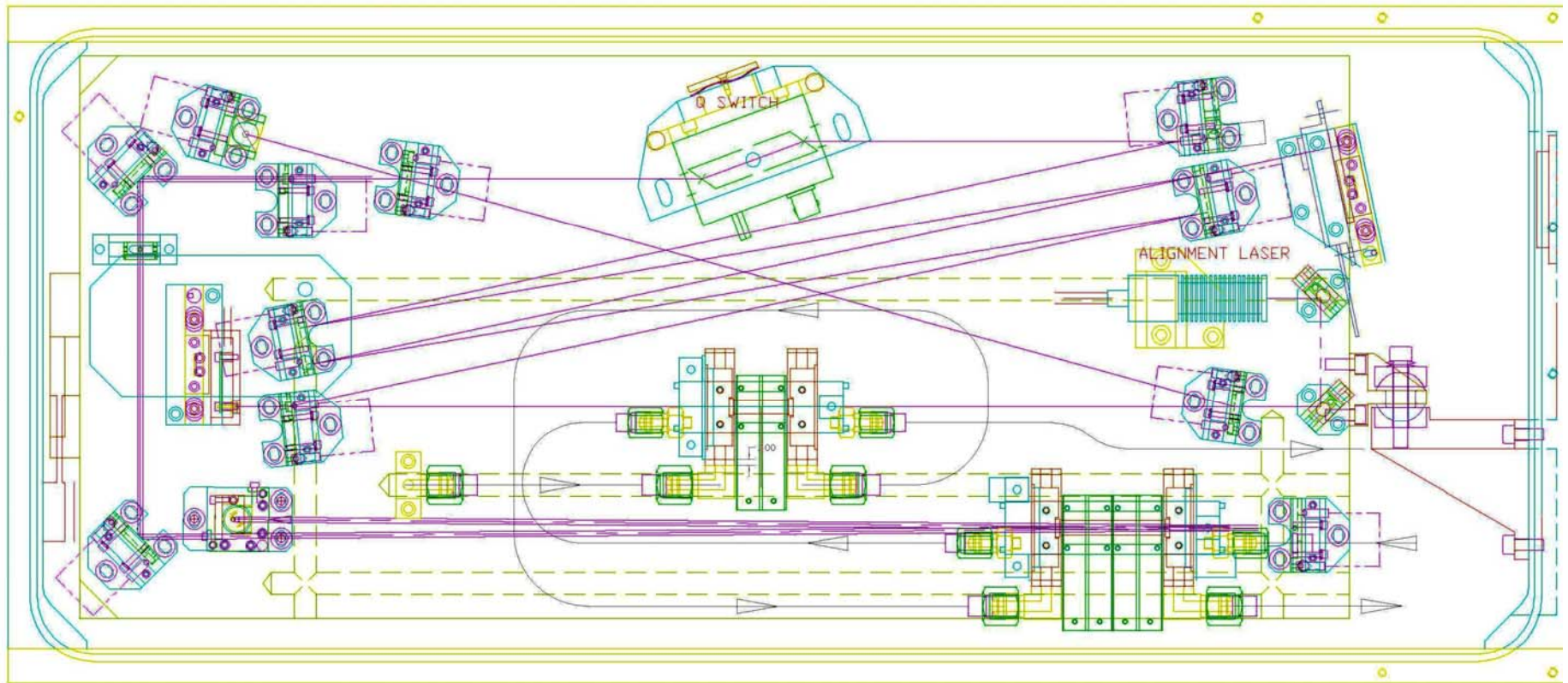


# Double pass amplifier performance



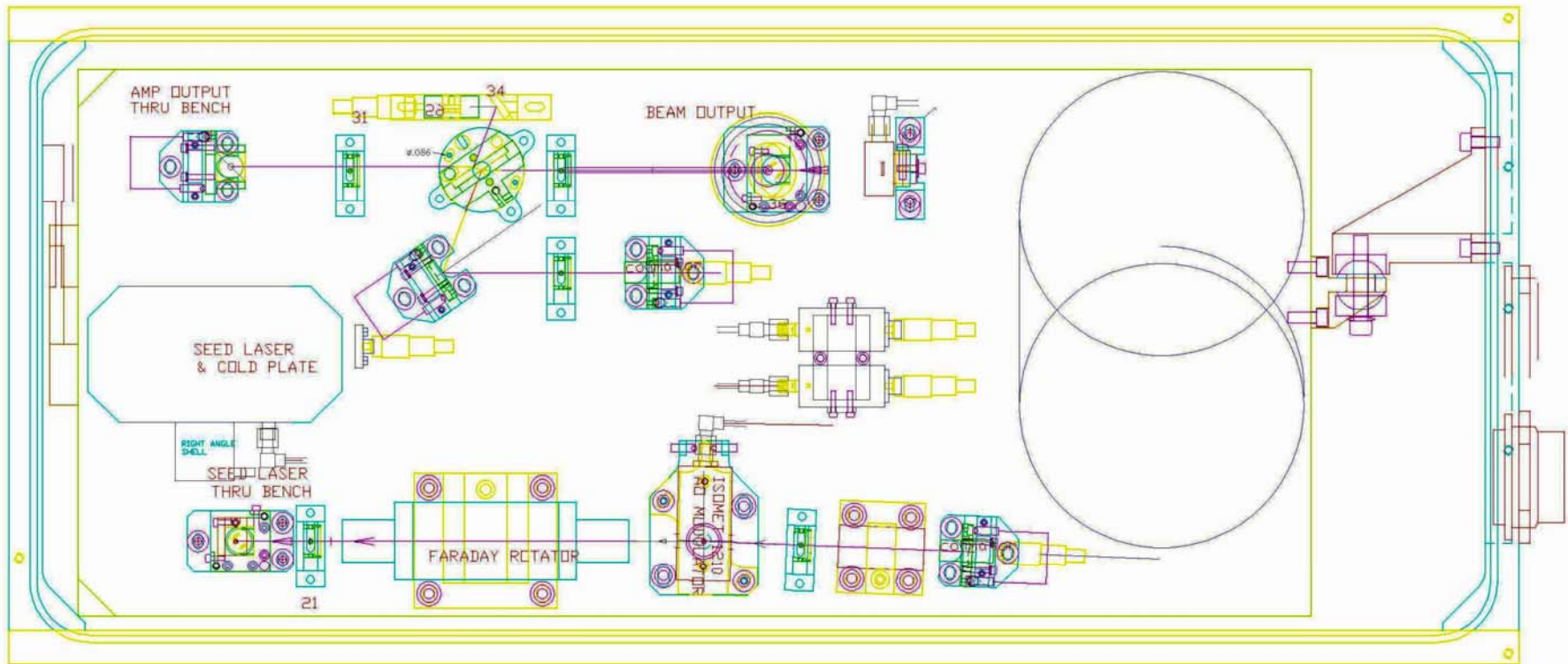


# Preliminary layout (side 1)





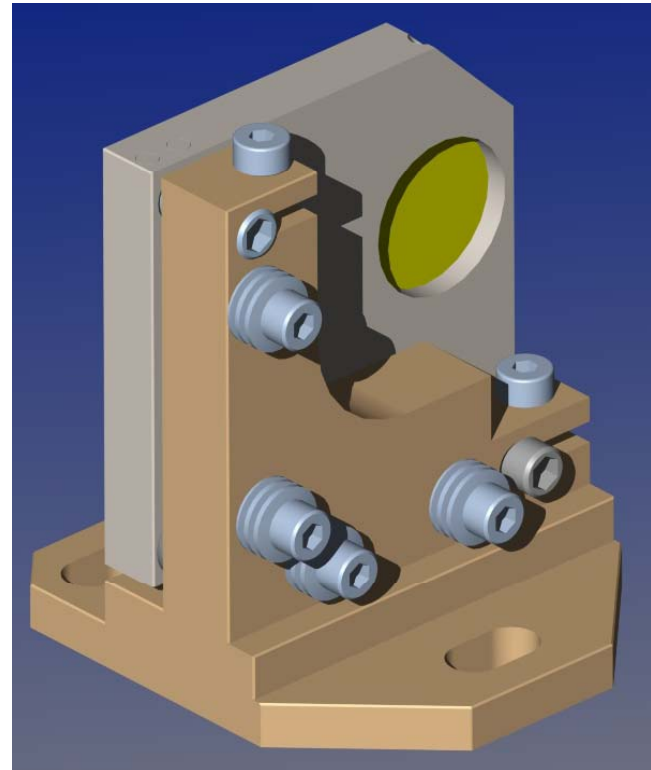
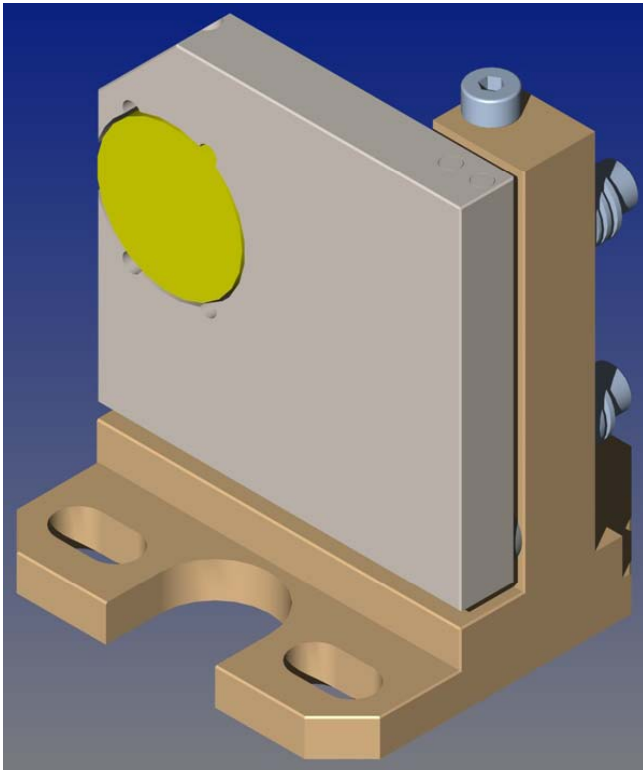
## Preliminary layout (side 2)







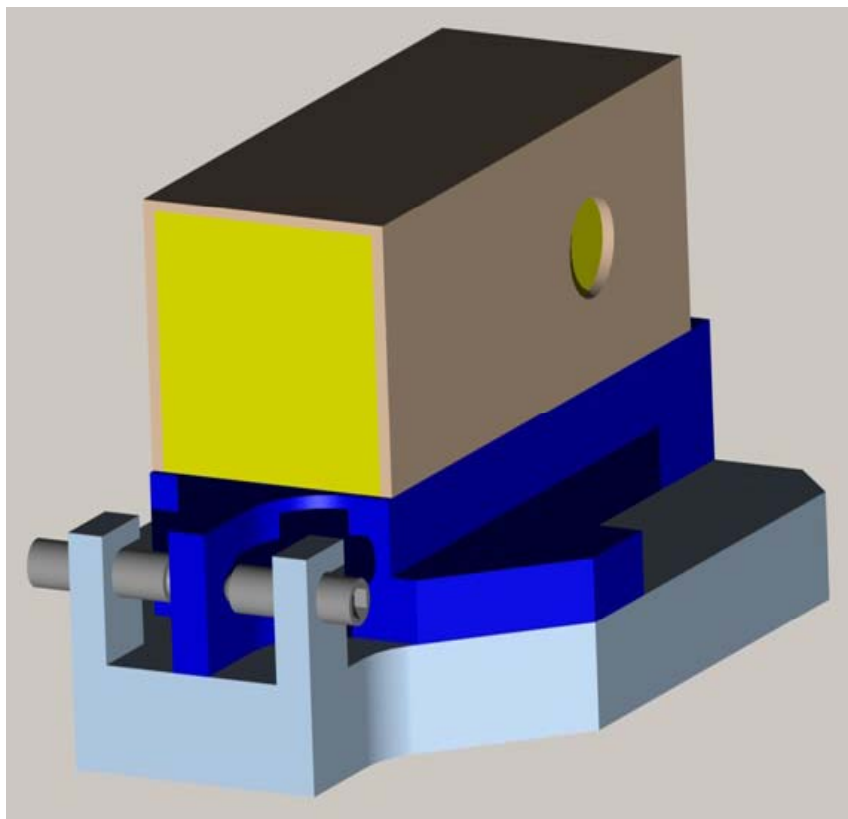
# Optical Mirror Mount





# Optical Component Mounts

AO modulator



Q-Switch

